

**Estimating Additional Water Yield From Changes in Management of
National Forests in the North Platte Basin
C.A. Troendle & J.M. Nankervis**

The Platte River EIS is examining alternative approaches to improving river flows in the Central Platte River for four threatened and endangered species (target species). Many different approaches to increasing basin storage of waters, management of waters, and retiming of river flows are being examined. Among the alternatives suggested during the scoping process is the concept of increasing the timber harvest on National Forests in the headwaters of the Platte River as a means of augmenting the water supply. This study is undertaken to provide a reconnaissance-level analysis of the water yield that might be expected from such an action.

In order for increased runoff from the National Forest to lead to improved Central Platte River flows for the target species, some fraction of the additional flows must be captured and allocated to the Recovery Program. The most likely means for this is capture and storage in a Federally operated reservoir. Due to the number of Federal reservoirs on the North Platte, as well as their relative proximity to the North Platte headwaters, it appears that focusing this study on the North Platte forests is a good test of the viability of this concept.

OBJECTIVES

Based on the Statement of Work, the objectives of this effort can be summarized as follows:

- 1) Review the current state of the art knowledge on the effects of forest and forest disturbance on water yield from the central Rocky Mountain Region.
- 2) Based on information provided by the U.S. Forest Service for the Medicine Bow, Routt, and Roosevelt National Forests; trends in forest stand condition, from 1860 to present, will be described and hydrologic simulation will be used to model the affects of those stand projections, or trends, on water yield from Forest Service lands in the North Platte River Basin.

- 3) Based on existing data and documents provided by the Forest Service, in concert with consultation with other Forest Service staff, determine the range of potential changes in water yield that could be obtained through prudent management of National Forest Lands on the North Platte River Basin. Any proposed silviculture prescriptions will reflect the laws, regulations, and policies that empower, direct, and constrain vegetation management by the U.S. Forest Service. The objective of the exercise will be to optimize timber production, maintain sustainability of forest ecosystem, and augment water yield.

A subset of objective 3 includes the simulation of the effect on water yield of an extensive beetle infestation to the spruce fir type and the occurrence of fire in lodgepole and ponderosa pine.

THE EFFECTS OF TIMBER HARVEST ON WATER YIELD; OR SUMMARY OF OUR KNOWLEDGE

More than 80 years of watershed research throughout the United States, much of which is specifically oriented toward the West, has demonstrated timber harvest, or vegetation removal, reduces net evapotranspiration (ET) and results in increased stream flow (Troendle and Leaf 1980; Bosch and Hewlett 1982; Callahan 1990; Stednick 1996). In the snow zone of the Rocky Mountains such increases have been documented following forest removal on experimental watersheds at Wagon Wheel Gap (Bates and Henry 1928; Van Haveren 1988) and at Fool Creek (Hoover and Leaf 1967; Troendle 1983; Troendle and King 1985) and Deadhorse Creek (Troendle and King 1987; Troendle and Olsen 1994) on the Fraser Experimental Forest in central Colorado. Other studies have shown similar responses in stream flow occur following deforestation due to insect epidemics (Love 1955) and fire (Troendle and Bevenger 1996). The magnitude of the observed changes in flow in the snow zone is similar in nature to those observed elsewhere in forested environments for similar levels of impact; although the distribution, or timing, of the flow change is more reflective of the dependence on snow melt (Troendle and Leaf 1980; Troendle and Kaufmann 1987; Troendle, *et al.* 1998). The sub alpine environment is also unique both in terms of the time of year when the flow change occurs, and in the persistence, or longevity, of the treatment effect (Troendle and Leaf 1980; Troendle and King 1985; Troendle and Kaufmann 1987).

In the snow zone of the Central Rockies, forest removal has been shown to reduce canopy interception losses in the winter months, resulting in greater snow pack accumulation (Wilm and Dunford 1948; Dietrich and Meiman 1974; Gary and Troendle 1982; Troendle and Meiman 1984; Potts, 1984; Gary and Watkins 1985; Troendle and King 1987; Meiman 1987; Schmidt and Troendle 1989; and Troendle and Reuss 1997). A similar reduction in interception loss (E), as well as reduced transpiration (T), occurs during the growing season following harvest (Wilm and Dunford 1948; Troendle 1987a; Troendle and Reuss 1997). The reduction in summer ET results in less soil-water depletion onsite, but it is only at the hillslope level that these wetter soils have, heretofore, been demonstrated to result in an increase in either late season base flow, or summer storm response (Troendle and Reuss 1997). This lack of demonstrated, late-season stream flow response to timber harvest is a reflection of the limited precipitation, causing the sub alpine forest to be water-limited in the late summer. The elevated soil-moisture levels in the harvested area, although not generally a demonstrated factor in influencing current season runoff, do play a significant role in response during the next snowmelt period. At that time, less melt-water is needed onsite to recharge the soil and excess melt-water becomes available for stream flow sooner (Troendle and King 1987; Troendle 1987b). As a result, changes in flow resulting from forest disturbance in the snow zone have always occurred on the rising side of the hydrograph, or early in the runoff season. In all snow zone studies, monthly flow change has been observed to consistently occur only in May and sometimes in June during snowmelt runoff (Troendle *et al.* 1998) with no detectable change during the balance of the runoff season. In addition, the largest increases in seasonal flow, following timber harvest, occur during the wettest years while the smallest increases in seasonal flow are usually associated with the drier years (Troendle and Leaf 1980; Troendle and King 1985, 1987; Troendle *et al.* 1998). These two factors mandate that adequate storage be available to make the increases in yield available when needed such as during periods of low flow. In contrast, the slow growth rate of sub alpine vegetation makes hydrologic recovery following timber harvest, or the return to pre-harvest flow levels, quite slow (Troendle and King 1985; Shepperd *et al.* 1991) and makes the efficiency and cost effectiveness of water yield augmentation seem quite attractive.

The first “paired” watershed study that looked at the effect of timber harvest on water yield occurred on the headwaters of the Rio Grande River at Wagon Wheel Gap, CO (Bates and Henry 1928). Stream flow from two

watersheds were monitored from 1911 to 1919 and then one of the watersheds was clear cut. Following harvest, stream flow was increased an average of 1 area inch for the following 7 years. The authors concluded the increased flow was largely a reflection of reduced winter interception loss and that although summer evapotranspiration (ET) by the over story was reduced it was largely offset by increased under story ET.

As noted by Leaf (1999), the most classic watershed experiment, in terms of both the length of record and the duration of treatment response, has been the Fool Creek Watershed on the Fraser Experimental Forest, CO (Hoover and Leaf 1967; Troendle and King 1985). Following a 12-year calibration with the control watershed, East St. Louis Creek, approximately 40 percent of the 714 acre Fool Creek drainage was harvested in alternating clear cut and leave strips during 1954-1956. The average hydrograph before and after treatment is depicted in figure 1. On average, total seasonal flow increased by 40 percent, average peak flow increased by 20 percent, and most of the detectable change in flow occurred in the month of May (Troendle and King 1985; Troendle *et al.* 1998). The largest peaks were not significantly increased and the largest increases in flow occur in the wettest or largest flow years (figure 2) (Troendle *et al.* 1998; Troendle and King 1985). In the case of Fool Creek, “bankfull discharge” increased from an average duration of 3.5 days prior to harvest to more than 7.0 days following harvest (Troendle and Olsen 1994). The most frequently occurring, or lowest, flows were not affected by timber harvest (Troendle and Olsen 1994). The response at Fool Creek, a small experimental watershed was similar to that of Wagon Wheel Gap and depicts the nature of the change that occurs when the forest in the sub alpine environment is disturbed by harvest, fire, or insect mortality. Fool Creek was harvested over 40 years ago and although the initial response to treatment has diminished as the Forest has recovered, full recovery is not expected to occur for yet another 25 to 30 years (figure 3).

Peak discharges expressed as either maximum instantaneous or maximum mean daily flow; from Fool Creek have always been observed to be snowmelt driven. This is consistent with Jarrett’s (1993) observations that floods occurring from watersheds lying above 7,500 feet in elevation in Colorado are snowmelt driven. Response to summers rainfall events generally represents only 3 to 4 percent of the event precipitation both before and after either timber harvest (Troendle and Bevenger 1987) or fire (Troendle and Bevenger 1995).

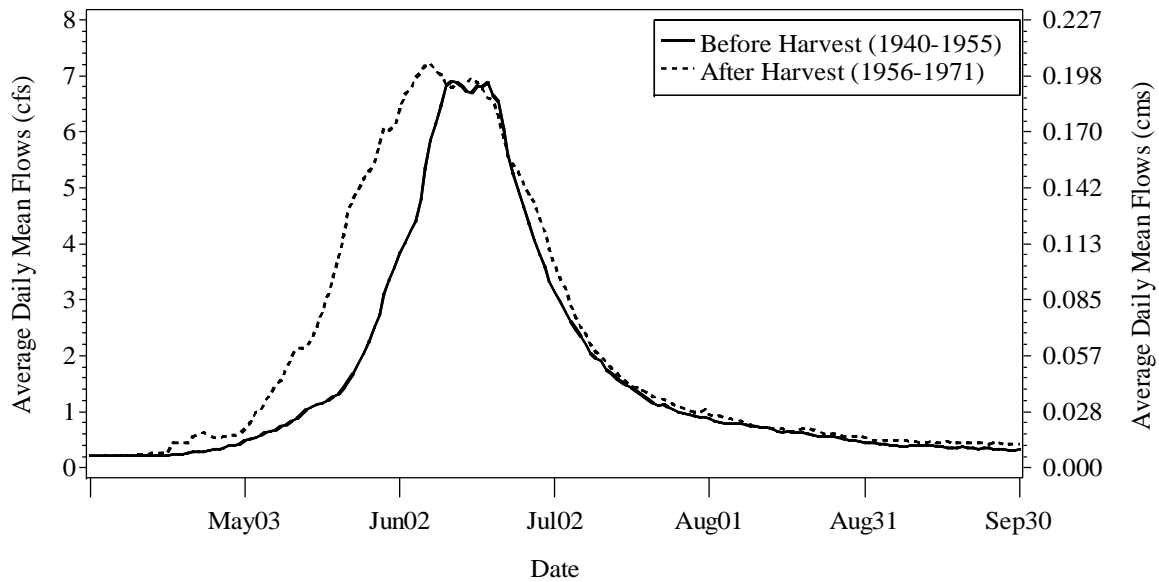


Figure 1: Seasonal mean daily flow for Fool Creek before (1940-1955) and after harvest (1956-1971).

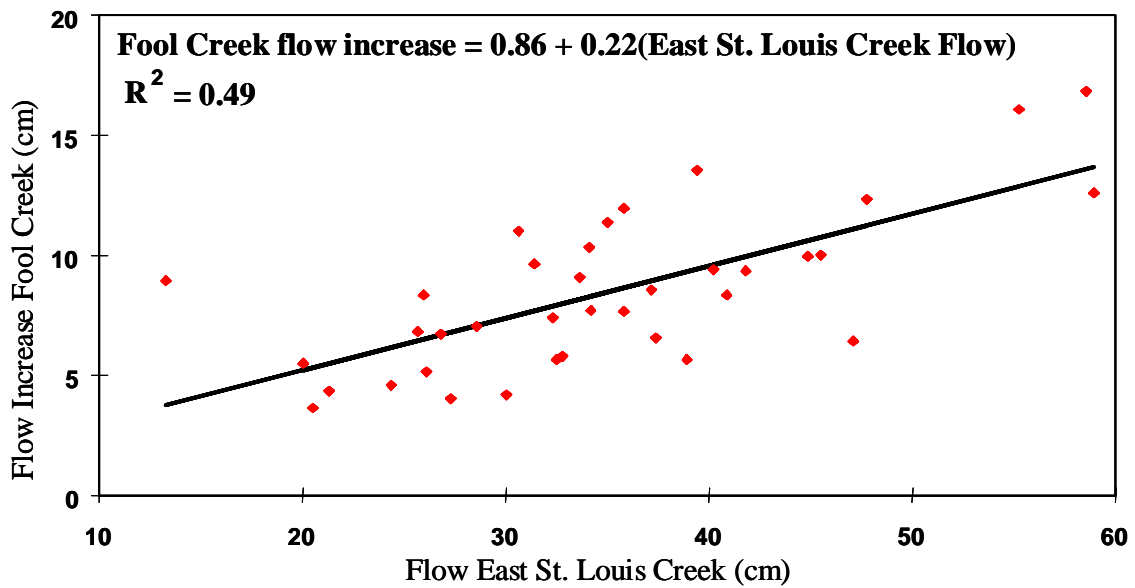


Figure 2. Increase in flow from Fool Creek expressed as a function of the total flow from East St. Louis Creek (increases are largest in the wettest years).

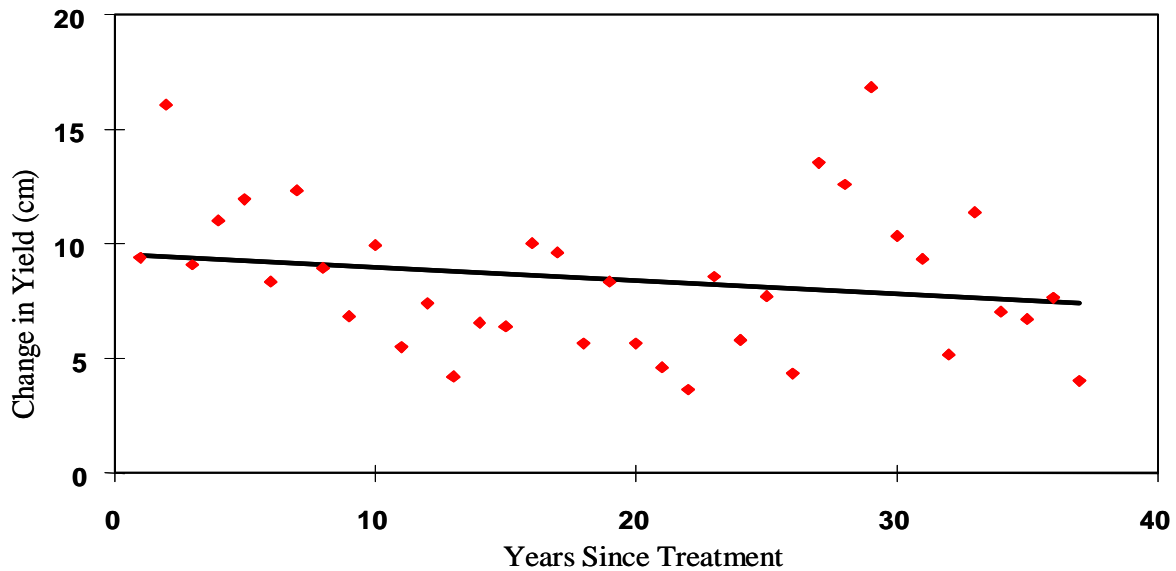


Figure 3. Increase in flow from Fool Creek plotted over years after Harvest.

Timber harvest on Fool Creek did not result in a significant increase in summer storm peaks, attesting to the assumption that in water limiting systems the late summer precipitation is used on-site with or without over story vegetation (Troendle 1987).

Observations made on Fool Creek, as well as other plot studies, at the Fraser Experimental Forest led to the development of a series of sub alpine water balance models that began in the 1970's. The first of these models, MELTMOD, simulated accumulation and melt of snow. This was followed by the WATBAL model, which incorporated MELTMOD, but in addition simulated a water balance for forest vegetation (Leaf and Brink 1973). The next generation model was LUMOD (Leaf and Alexander 1975), a land use simulator that incorporated output from an even-aged growth and yield model (RMYLD) (Edminster 1978) in the WATBAL model to simulate water yield responses to clear cutting.

These early models assumed that clear cutting had the greatest impact upon snow pack accumulation, because at the time it was believed that the measured increase of snow, present in openings following timber harvest, was the result of increased deposition during the snow fall event and redistribution of snow intercepted in the surrounding canopy, between events. This relationship was incorporated in the models as a "Rho" distribution function (see Troendle and Leaf 1980) in which snow retention in the opening (or accumulation) was a factor of opening size. Thus, the

early models were most sensitive to clear cutting and a minimal or zero increase in water yield was assumed to occur under partial cutting unless more than 50 percent of the over story vegetation was removed, (Troendle and Leaf 1980). The Deadhorse Creek Watershed experiments were implemented to test both the hypothesis and the initial hydrologic models.

Deadhorse Creek, gauged since 1955, is a 667 acre watershed (figure 4) on the Fraser Experimental Forest. Two separately gauged sub drainages within Deadhorse Creek are the 100 acre North Fork and the 193 acre Upper (south) Basins. Weirs on the North Fork and Upper Basin were built in 1970 and 1975, respectively. The Deadhorse Main watershed and two sub drainages are calibrated against the 1984 acre control watershed, East St. Louis Creek. Unit 8, on Deadhorse Creek (figure 4) is an un-gauged North Slope, 100 acres in area, which lies downstream of both the North Fork and the Upper Basin sub drainages. Unit 8, or the North Slope, represents a portion of the 368 acre interbasin area lying below the two gauged sub drainages and above the main streamgage.

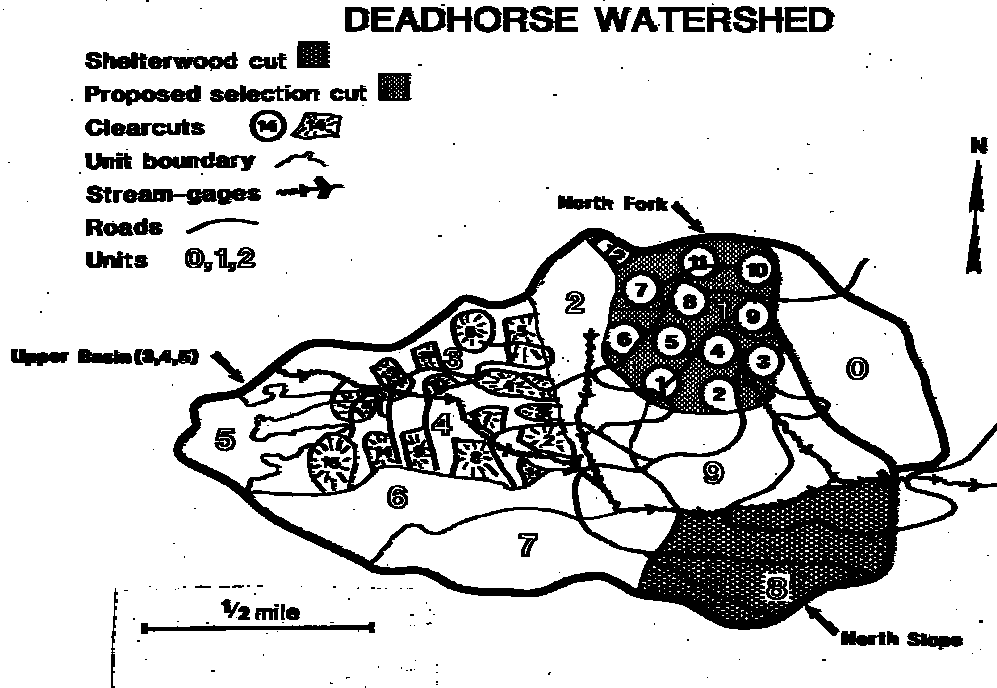


Figure 4: Schematic drawing of the Deadhorse Creek watershed showing harvesting practices and streamgage locations.

The Deadhorse Creek Watershed and its sub drainages were used as pilot demonstration areas to evaluate management strategies that represented ca 1980 thinking on increasing water yield through timber harvest. The circular clear cuts imposed on the North Fork, and the irregular clear cuts in the Upper Basin (figure 4), were expected to result in an increase in flow. The shelterwood cut imposed on the North Slope was not expected to result in a significant increase in flow. The first treatment imposed on Deadhorse Creek occurred on the North Fork sub drainage in 1977. Timber was removed on 36 percent of the land area (figure 4) by commercially clear cutting 12 small circular units, uniformly spaced through the drainage. The circular openings were about 5H (H= tree heights) in diameter, and occupied about 3 acres each. Harvesting was completed in the summer of 1978. During the summers of 1983 and 1984, approximately 30 percent of the Upper Basin was harvested in irregular-shaped clear cuts, varying in size from 1-15 acres. Approximately 95 percent of the basal was removed in the clear cuts on both sub drainages. The residual basal area represented either non-commercial trees or advanced regeneration. Some snags were left standing to provide wildlife habitat.

The 5H circular clear cuts imposed on the North Fork were intended to maximize snow pack accumulation in the clear cuts and to optimize flow increases for the basal area removed (Troendle and Leaf 1980). The irregularly shaped openings placed in the Upper Basin were designed to blend with the surroundings and create less visual impact than the circles, increase edge effect for wildlife, and result in increased snow pack accumulation and water yield. In contrast, it was reasoned that partial cutting, as proposed for the North Slope, Unit 8, would have little effect on stream flow because: (1) in a semi-arid environment such as the sub alpine (Leaf 1975), the residual stand would have access to and use any transpiration savings during the growing season; and (2) without clear cutting and the attendant aerodynamic changes in the canopy there would be no redistribution of snow and no net change in the deposition pattern of the winter snow pack; thus the efficiency in delivering water to the stream would not be enhanced. The hypothesis resulting from these assumptions were that the partial cutting (harvesting by individually marking trees for removal or thinning) would be far less efficient in increasing stream flow than would be the removal of the same percentage of the forest in small (5-8H) clear cuts as imposed on both the North Fork and Upper Basin.

To evaluate this hypothesis, an area equal in size to the North Fork (100 acres), was partially cut, removing approximately the same percentage of the forest by individually marking trees. Unfortunately and unlike the North Fork sub drainage, Unit 8 is not independently or directly gauged. The measured flow from the Upper Basin and the North Fork must be subtracted from the flow measured at the Deadhorse Main streamgage to partition out of the flow from the interbasin area, which includes the contribution from the North Slope. Partitioning the flow increases the opportunity for error and decreases the reliability of the experiment, but was done out of necessity to assess response from the North Slope (Unit 8) and only for the period 1981-1983. After 1983, the combined response of treatments from both the North Fork and the Upper Basin make detection of the hydrologic effect of the North Slope (Unit 8) treatment even more tentative.

Not all of the observed responses, were as expected. Peak water equivalent increased in the openings on the North Fork by 18 percent as expected (Troendle and King 1987). Although a significant increase in snow pack could be documented within the openings, the increase did not significantly increase the overall mean for the watershed (Forest plus open). On the Upper Basin, openings are more wind exposed, resulting in a certain degree of scour, and increases in snow pack accumulation at the level of the openings cannot be documented. The real surprise however, was that Peak Water Equivalent in the snow pack on the partially cut North Slope increased 16 percent, representing a 4.8 cm or 1.9 inch, increase snow in water equivalent over the entire 100 acre unit (Troendle and King 1987).

Total water yield increased on the North Fork (figure 5) as expected but increases have occurred only periodically on the Upper Basin (figure 6). In the case of the North Fork, increases have averaged 2.5 – 3 inches per year for the period of study. In the case of the Upper Basin, the clear cuts were not as effective in generating an increase in flow. On average, covariance analysis indicates flow has significantly increased, but not all individual yearly responses show that trend. In drier years, flow is not increased detectably (figure 6) on the upper basin. Both the North Fork and the Upper Basin demonstrate that the largest increases occur in the wettest years and that most of the increase occurs in May.

The surprise was the response from the North Slope (Unit 8). Partial cutting, or thinning, the stand resulted in a 3.5-inch increase in flow for the period 1981-1983. Over 50 percent of the observed increase in flow can be

attributed to the increased snow pack accumulation under the canopy (Troendle and King 1987) following timber harvest.

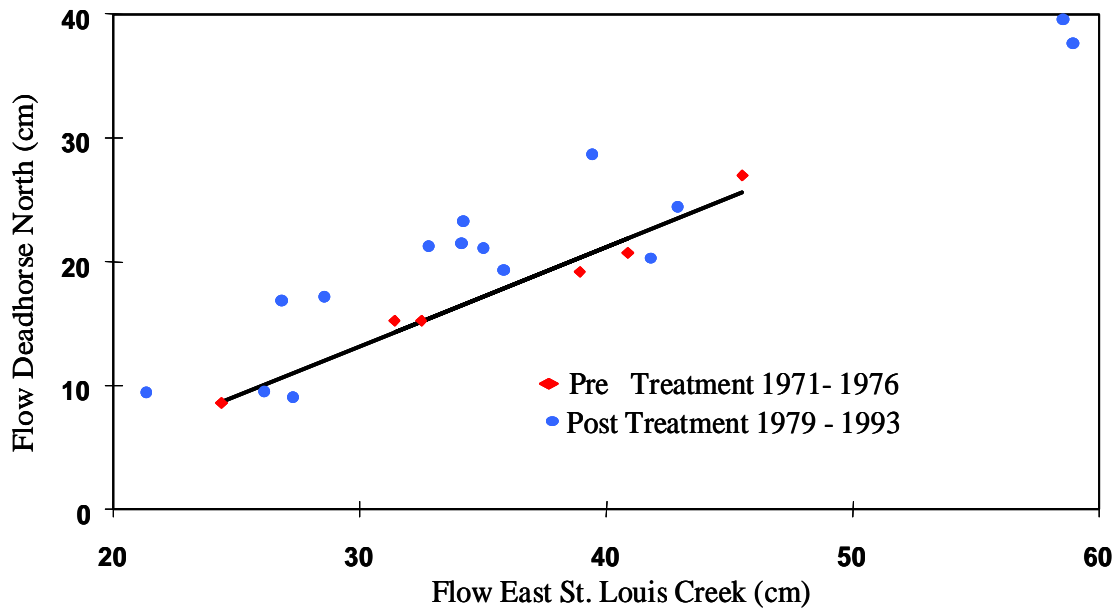


Figure 5. Regression line demonstrating the relationship between streamflow from Deadhorse North plotted over streamflow from the control watershed, East St. Louis Creek. Pre- and post- harvest data are presented.

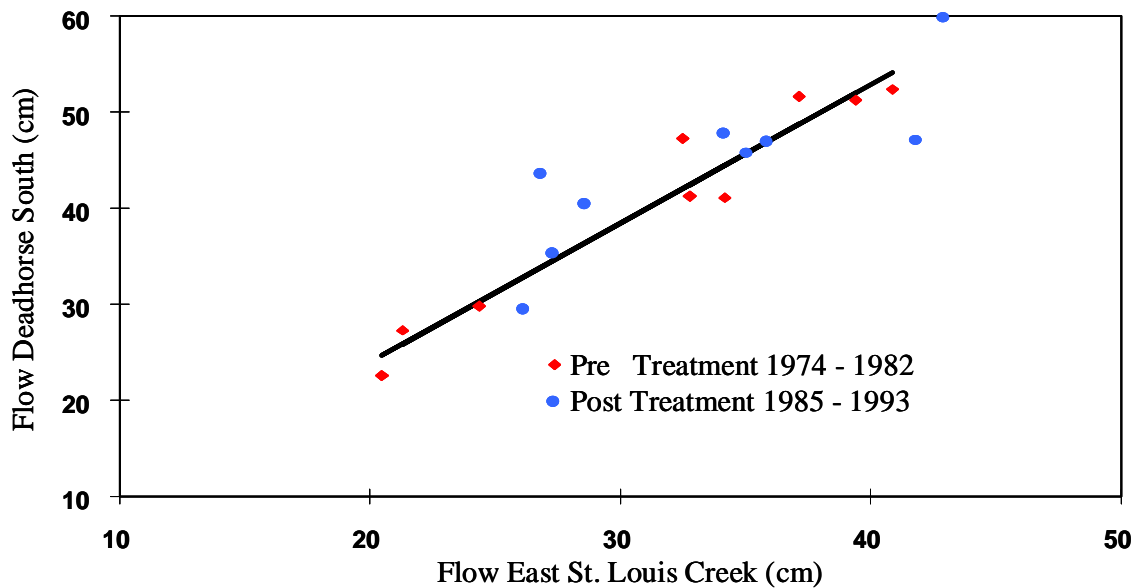


Figure 6. Regression line demonstrating the relationship between streamflow from Upper Basin plotted over streamflow from the control watershed, East St. Louis Creek. Pre- and post- harvest data are presented.

Cumulatively, approximately 18 percent of the basal area has been removed from the Deadhorse Creek watershed above the main streamgage, as a result of the three treatments. Although significant increases in flow have been documented to occur at the level of the individual sub-basins, significant changes in flow cannot be detected at the main streamgage (figure 7). Noted earlier, the flow increase observed to have occurred incrementally from the North Fork, Upper Basin, and North Slope (Unit 8) portions of Deadhorse Creek were not, in aggregate, detectable a few hundred yards downstream at the mouth of the main watershed. As watershed size increases, the changes in flow documented to occur at the point of impact, or on-site, become less detectable. The argument cannot be made that the observed increases in flow are not present downstream, but their presence is difficult to document.

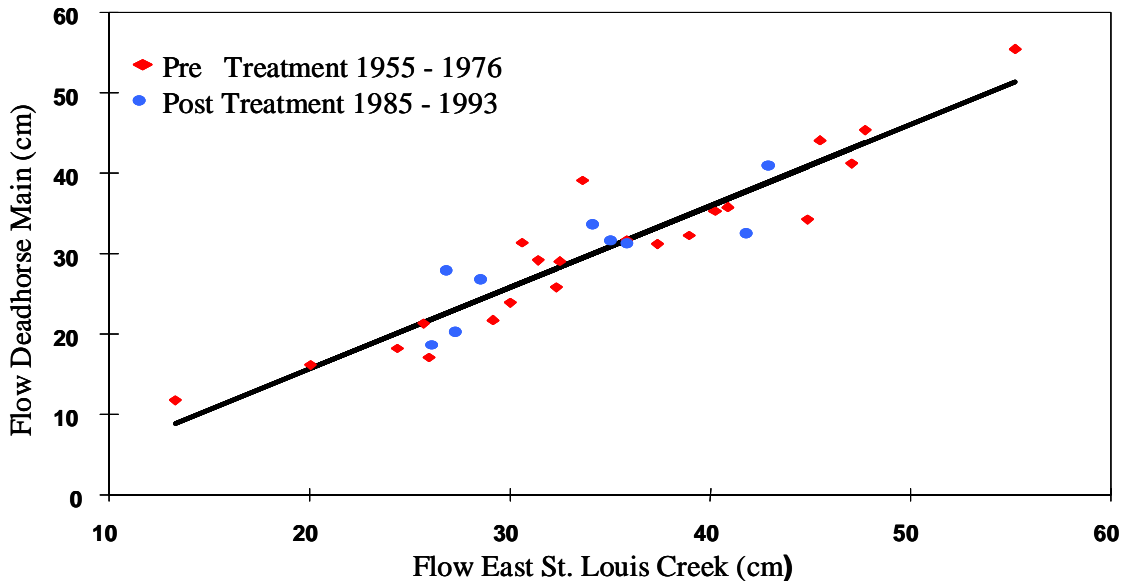


Figure 7. Regression line demonstrating the relationship between streamflow from Deadhorse Main plotted over streamflow from the control watershed, East St. Louis Creek. Pre- and post- harvest data are presented.

In the early 1980's, preliminary results from the Deadhorse Creek Watershed study rekindled studies exploring the effect of forest vegetation on snow pack accumulation. At least two processes contribute to this increase in snow pack within cut stands. Wilm and Dunford (1948) attributed the increase to a reduction in evaporation of snow intercepted by the tree crowns. Measurements by Goodell (1959) supported this conclusion. However, when (limited) snow pack measurements on the Fool Creek watershed demonstrated no net increase in peak water equivalent after

harvest, Hoover and Leaf (1967) suggested that snow intercepted in the adjacent canopy was redistributed into clear-cut blocks by wind, with little or no evaporation loss. Hoover and Leaf (1967), Leaf and Brink (1973) and later Troendle and Leaf (1980) assumed redistribution of snow, rather than reduced interception loss, was credited for the increase in snow pack in forest openings. But, with 18 years of additional record, Troendle and King (1985) found there was an overall increase of 9 percent in peak water equivalent on the Fool Creek watershed (significant at the one percent level). This finding supported the original explanation (Wilm and Dunford 1948) that reducing interception loss is an important factor in manipulating snowmelt runoff by harvesting timber. The 9 percent increase at the watershed level supported the argument that the average 30 percent increase in the openings reflected an interception reduction rather than redistribution from adjacent forest (Troendle and King 1985).

Subsequent efforts to further quantify the roles of interception loss and wind redistribution on snow pack accumulation include a study by Wheeler (1987) comparing snowfall in a clearing with snowfall in the surrounding forest. Wheeler (1987) frequently measured accumulation on a grid of snowboards and determined that most of the increase in accumulation in the opening occurred during storms (confirming earlier findings of Troendle and Meiman 1984, 1986). Between storms, observations indicated little snow was added to the clearing, from the adjacent forest, by wind (Wheeler 1987). The magnitude of the forest-to-clearing difference in accumulation decreased, however, with increasing wind speed during storms indicating that interception and subsequent evaporation losses are reduced with increased wind speed during the event.

In summarizing the effects of partial cutting on snow pack accumulation, Troendle (1987) developed a linear relationship between increases in snow pack accumulation and basal area (reduction) of the stand. On average, maximum interception loss is reached at a basal area approaching 100 ft² acre⁻¹. Based on the results of eight separate experiments spanning nearly 50 years of study, and including observations in the watershed experiments mentioned earlier, Troendle (1987) also developed a relationship between percent basal area removed and percent increase in snow pack accumulation. This general relationship has since been partitioned into responses specific to north, south, or east and west slopes (see Schmidt and Troendle 1989; Schmidt *et al.* 1998; Troendle *et al.* 1991).

In addition, the effect of forest density changes on summer evapotranspiration has also been better defined than in earlier models (Troendle 1987; Kaufmann *et al.* 1987). Partial cutting or thinning can result in reduced transpiration in the summer; however, the efficiency in delivering an increase in flow to the stream channel is a function of seasonal precipitation. In average or wet years, reduced basal area resulted in less soil water depletion and an increase in water available for stream flow; however, in below average precipitation years, the residual vegetation used the available water. In all cases, water use per unit of residual basal area or leaf area index increased dramatically; as a result, total water use by the remaining vegetation increased. Observations at the plot level support and help interpret the responses observed in the watershed experiments.

Since the early 1980's, process studies have documented much more about the interaction between forest canopy and snow pack accumulation. Small patch clear-cuts are no longer considered the only long-term harvesting practice for water yield augmentation. This improved understanding has been incorporated in a revision of the sub alpine water balance model WATBAL so that we may now simulate evapotranspiration changes, summer and winter, and project water yields as a function of any forested condition or silvicultural activity. Input data for the revised WATBAL model include slope, elevation, aspect, average precipitation, and basal area by species for the forested area being modeled (Shepperd, *et al.* 1991 and Troendle 1991).

As Leaf (1999) noted, the technology does exist to increase water yield through timber harvest and as he infers, the corollary exists that increasing forest density to the level of complete hydrologic utilization for the site will result in flow reduction (Troendle and Leaf 1980). Shepperd *et al.* (1991) simulated that in a "no harvest" alternative of mature stands of either lodgepole pine or spruce-fir that represented stands already at complete hydrologic utilization, long-term water yield projections were largely unaltered because forest succession caused species composition and structure to change with minimal change in either stand density or water yield. Assuming the acreage of the landscape that is in forest is not altered, one would not expect to observe changes in flow at the streamgage as a result of already mature forest stands succeeding to their climax state (Shepperd *et al.* 1991).

One of the more significant issues regarding water yield augmentation is the limited experience we have in applying research based technology at the landscape level in forest and wild land management. The last formal assessment of the potential for water yield augmentation through forest and range management was by the American Water Resources Association in the early 1980's (Ponce 1983). Douglass (1983), Harr (1983), Kattelman *et al.* (1983), and Troendle (1983) presented regional summaries of the opportunity to increase water yield through forest management based on what was ca 1980's technology. In a summary manuscript, Ponce and Meiman (1983) concluded that the opportunity to augment water yield through timber harvest, as a large-scale land management program, may not be as great as would be implied based on small research watershed results because of the diversity of land ownership patterns and the conflicting physical, biological, and administrative constraints associated with implementation of the technology.

However, because of the limited supply and high value of water in the Rocky Mountain West, interest arose in the early 1980's in demonstrating that the water yield augmentation technology, demonstrated to work on small-scale experimental watersheds, such as Fool Creek and Deadhorse Creek on the Fraser Experimental Forest, could be applied at an operational or landscape scale by forest managers and yield similar results.

The impetus for the project came from the Regional Forester (USFS), Region 2, whose objective was to develop a water yield augmentation initiative in the Rocky Mountain Region that would demonstrate an operational application of what was then current research technology. A necessity was to find a significantly large area to demonstrate that research results from small watershed experiments could be extrapolated to the operational level while involving a range of users and interest groups during implementation. Coon Creek was selected as the project area primarily because the watershed in which it is located, the East Fork of Encampment River, was a large, uncut, and non-roaded watershed of the size necessary for evaluating the hydrologic impacts of a commercially viable timber sale. The basin consists of two contiguous watersheds of comparable size, aspect, and timber types, allowing a paired watershed study. The treatment watershed, Coon Creek, could be logged by conventional harvesting methods using standard silvicultural practices (small clear cuts) of the times.

Prior to selecting Coon Creek, an intensive search for a suitable area was made throughout Region 2 and a portion of Region 3 of the Forest Service. Initially, it was hoped that an area could be selected that involved ownership by several government agencies, the state, and the private sector – a true partnership. Initial discussions in the late 1970's and the early 1980's included the Denver Water Department, USDI Bureau of Land Management (BLM), USDA Soil Conservation Service (now NRCS), Colorado Division of Wildlife, Colorado Forest Service, and the State Engineer's Offices in Colorado and Arizona, as well as the Regional Foresters in Regions 2 and 3 (Troendle 1990). As the search for a site proceeded, the site in Wyoming proved to be the only site available to meet technical objectives of the demonstration. In contrast to the perception that extensive areas exist for the application of the water yield technology, search for the demonstration site presents testimony to the fact extensive land areas suitable for water yield augmentation are not readily available on National Forest System (NFS) lands in the inland west.

Coon Creek, the treatment watershed, is a 4133 acre drainage located in the Sierra Madre Range on the Hayden District of the Medicine Bow National Forest (MBNF) in Wyoming. In 1982, 8-foot Cipoletti weirs were constructed on each drainage to monitor stream flow. By 1987, a suitable calibration had been achieved (Bevenger and Troendle 1987) and design and implementation of the treatment began. Initially the intent was to harvest approximately one-third of the Coon Creek watershed, as was done in research at Fraser Experimental Forest. However, this was an operational effort and technical considerations, as well as compliance with resource constraints imposed by the MBNF Forest Plan (primarily for minimizing impairment of visual quality as well as riparian and old-growth protection), reduced the opportunity for harvest. Although minimal in nature, these considerations and constraints resulted in only 24 percent of the watershed area actually being impacted by either road construction or timber harvest.

Although the length of the post-treatment record for Coon Creek is short (5 years), the impact the treatment had on seasonal water yield is quite clear. Removal of vegetation from 23.7 percent of the area significantly increased flow by an average of 3.0 inches (Troendle *et al.* 1998). The increase is proportionally consistent with what has been observed to occur on small experimental watersheds elsewhere, and extrapolation of empirical estimates of change, based on process research at the Fraser Experimental Forest (Troendle and Reuss 1997), compare well with the observed changes at

Coon Creek. The calibration relationship, as well as pre- and post-harvest seasonal flow values are presented in figure 8. Flow was significantly increased as a result of timber harvest, but it should be noted seasonal increases in flow only slightly exceeded the significance detection limit. Generally, it has been assumed that 20-25 percent of the vegetation on a fully forested small watersheds has to be harvested in order to generate a detectable response at the streamgage. Approximately 24 percent of the vegetation on the Coon Creek watershed was harvested and the increase is slightly above the detection limit. In addition, in an attempt to harvest as much of the area as possible, many of the clear cuts crossed interior ridges, as they did on the Upper Basin at Deadhorse Creek, causing a certain degree of wind scour. Snow pack accumulation in the openings was not increased on Coon Creek (Troendle *et al.* 1998) and there may be actual decreases in net accumulation on the watershed in wetter years as a result of exposure to wind. (Troendle and Meiman (1984) observed that once slash or roughness, filled with snow, retention efficiency in openings decreased).

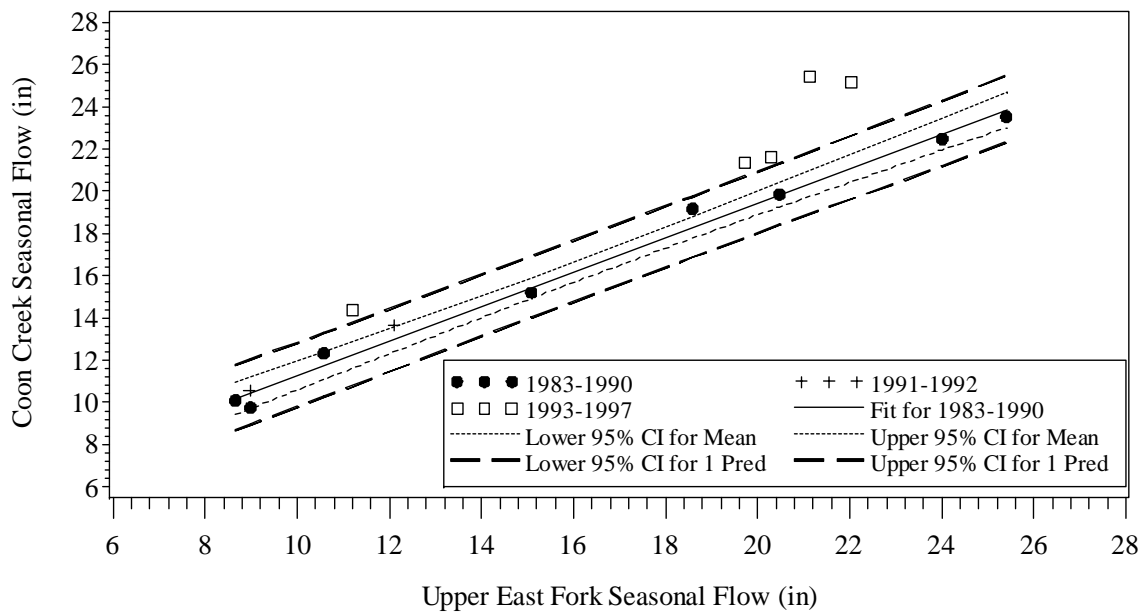


Figure 8: Seasonal water yield for Coon Creek watershed (harvested) plotted over that for the Upper East Fork (control). Pre-harvest, harvest, and post-harvest data are presented.

Understanding the dynamics of stream flow response to timber harvest is critical to evaluating the opportunity to increase flow via timber harvest and equally critical in assessing the effects of forest regrowth on historic flows.

Fool Creek, the small (714 acre) experimental watershed on the Fraser Experimental Forest, described earlier, represents one of the most definitive data sets world-wide; documenting both the initial effect of timber harvest on increasing water yield, and the more subtle reduction in the initial increase in water yield that occurs as the vegetation recovers or re-grows over time. Figure 9 represents a double-mass plot (Anderson 1955) of cumulative flow from Fool Creek (the treated watershed) plotted over the cumulative flow from East St. Louis Creek (the control watershed). The data for the period 1943-1955 (Point A to B on figure 9) represents the pre-harvest, or calibration, period and as can be noted, the relationship is linear (follows a very straight line), and a regression line has been fitted to the calibration data and extended to point C (equality, or a 1:1 relationship, is not required). In 1954-1956, 40 percent of the watershed area was harvested on Fool Creek and resulted in an average increase in flow of 40 percent. The increase in flow from Fool Creek began immediately. This abrupt change in the relationship between Fool Creek and East St. Louis Creek, as a result of the increase in flow from Fool Creek, can be evidenced by the change in the trajectory of the double-mass plot at point B. Flow increased on Fool Creek (Y-axis) relative to that for East St. Louis Creek (X-axis) causing the relationship to deflect upward. Since 1956, the clear cuts on the Fool Creek watershed have gradually recovered naturally. By 1984, approximately one-third of the original vegetation biomass had returned. By 1995, approximately one-half or more of the original increase in flow had been lost as a result of regrowth. Regrowth can be documented by the gradual, almost imperceptible, arc present in the double-mass plot between points B and C (figure 9) as the flow returns to the relationship that existed prior to harvest. Eventually, we would expect the double-mass plot to parallel the regression (solid) line fitted to the pre-harvest data. If the recovery line “over compensates”, it would imply the younger, more vigorous stand is using more water than the original stand.

The Fool Creek watershed experiment sets the standard in the snow zone for hydrologic comparisons that document the effect of forest disturbance on stream flow response both in terms of initial response and the recovery. Data from highly controlled experimental watersheds, such as Fool Creek, are usually more definitive in demonstrating response than are landscape scale watersheds, normally monitored with less rigor and for largely forecasting purposes.

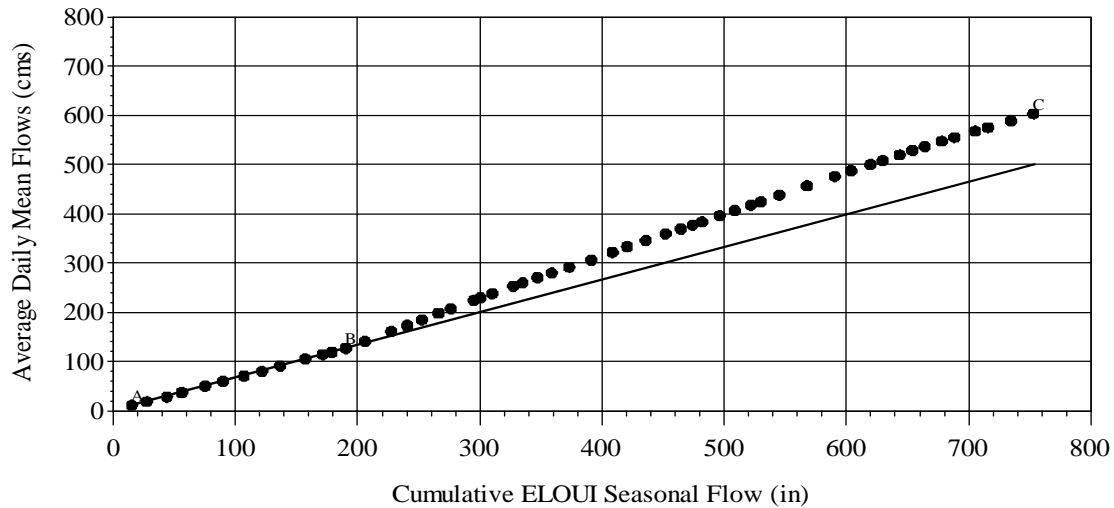


Figure 9: Cumulative discharge from Fool Creek (harvested) plotted over the cumulative discharge for East St. Louis Creek (control) at the Fraser Experimental Forest. A represents the beginning of measurement (1943), B represents the abrupt impact of harvest (1955), and C represents 1996.

As an example of the problems associated with defining the response from timber harvest at the landscape scale, Kircher *et al.* (1985) evaluated those factors most responsible for influencing natural stream flow characteristics in western Colorado watersheds. Based on analysis of the long-term record from 123 USGS gauging sites in western Colorado, only drainage area and mean basin elevation were found to be significant parameters in predicting mean annual flow. Percentage of the total watershed area in forest, or percentages of watershed area in other land use categories, were not a significant parameter in predicting either annual mean flow or any other stream flow characteristics Kircher *et al.* (1985) and others elsewhere have been unable to show that the percentage of watershed in forest is correlated with stream flow at landscape scale. In landscape scale watersheds, such as those gauged by the USGS, forested area is often only a portion of the total area. If the actual amount of forest vegetation is not well correlated with flow at this level, change in the density of vegetation is equally unlikely to be related as well. One can assume that detecting the effect of subtle changes in forest vegetation over time, even where they occur, would be difficult. As part of ongoing work (unpublished) by C. A. Troendle to develop improved flood forecasting equations for western Colorado and Wyoming, the percent of forested area in the watershed did not prove to be significant in describing peak stream flow response at the landscape level; i.e., using USGS stream flow data. At the landscape scale, many factors influence stream flow generation, including the variance and errors associated with monitoring flow at this scale and resolution; all of which

make documenting the role of vegetation on stream flow response at the landscape level a difficult and often misleading task.

For example, Burton (1997) used USGS stream flow records to assess the cumulative impact of timber harvest activities (which occurred over a 12-year period) on stream flow from Brownie Creek in Utah. Using the North Fork of Dry Creek as the control, Burton (1997) compared the flow for the pre-harvest period (1951-1960) with the flow for the harvest/post-harvest period (1961-1980) for both watersheds and found flow for the 1961-1980 period was significantly greater on Brownie Creek. He concluded the increase was a response to timber harvest. Troendle and Stednick (1999), in a reanalysis of the same data found moving the streamgage location on Brownie Creek in 1960 was more likely the cause of the abrupt change in measured flow (figure 10). The abrupt flow change Burton (1997) detected did occur, but it occurred entirely in 1960 as an artifact of relocating the streamgage and not a reflection of the timber harvest operations that occurred over the next 12-year period (1960-1972). If harvesting were the cause of departure, the change would have been subtle and accumulative over the 12-year period; opposite of the trend in figure 9.

Figure 10 presents a comparison of the cumulative flow from Brownie Creek plotted over that from North Fork Dry Creek. In 1960, an abrupt change in the relationship between the two streams occurred as an artifact of streamgage relocation. Because the line is quite linear from 1960 to 1980, one cannot conclude that further increases in flow occurred as a result of the continuous harvesting activities that occurred from 1961-1972. If timber harvest caused the change, one would expect to see a gradual arc evident in the double-mass plot (figure 10).

Leaf (1999) used a combination of long-term USGS stream flow data and NRCS snow-course data to document what he also considered to be the long-term effect of vegetative re-growth or in-growth, causing diminished stream flow in the North Platte River Basin. Leaf (1999) utilized records from the North Platte River at Saratoga, Wyoming, the North Platte River at Northgate, Colorado, and the Laramie River at Woods Landing, Wyoming. In his Table 3, Leaf (1999) summarized analysis of the three gauge records and documents decreases in flow at all three stream gauging stations. His inference is that increased forest density caused a measurable decrease in stream flow. There is no question that increases in forest density cause a

decrease in flow; the question is whether or not the change can be detected at an off-site streamgage.

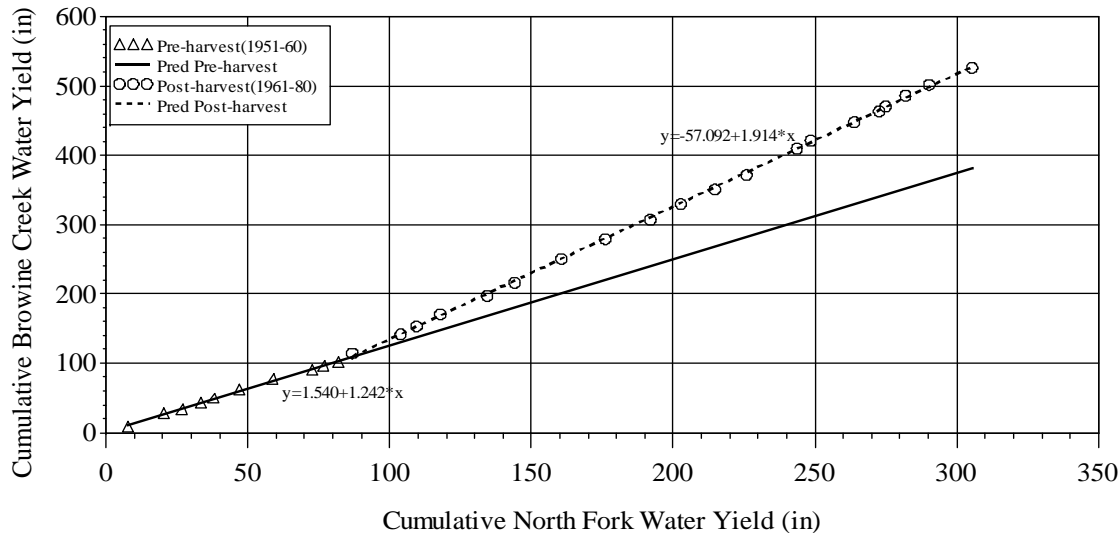


Figure 10: Cumulative annual water yield for Browne Creek plotted over that for North Fork of Dry Creek. The Browne Creek streamgage was relocated in 1960. Harvest occurred on Browne Creek from 1960-1972 and effect is not evident.

As noted earlier, the primary objective of this effort is to address the application of existing water yield augmentation technology to the “suitable and treatable” NFS land in the North Platte River Basin and quantify the potential for augmentation through timber harvest. At the outset, it should be noted that even Coon Creek, where water yield augmentation was the primary focus and dedicated use of the land, less than 24 percent of the total watershed area could be impacted. The initial intent was to harvest one-third of the watershed area in order to mimic the experimental watershed treatments. Even though the Coon Creek project was minimally constrained by concern over other resources, operational constraints in the forest plan limited the harvested area to less than 24 percent of the watershed area.

In managing public lands, the USFS must address the potential impact of any proposed alternative on numerous resources. Figure 11 represents a simple schematic showing the relative impact of various harvesting practices on the value of various resources, including water. There are tradeoffs, and as can be inferred from Figure 11, not all resource needs can be met on a given site. Patch clear cutting (PC), for example, appears to maximize water yield, per acre harvested, but it is very detrimental to several other resources currently considered important. Patch clear cutting cannot be applied to all

acres. Land managers must recognize the potential multiple-use values of each area, determine primary and secondary uses, and then select the management alternative that will enhance or protect those values. On any individual site it is likely, even probable, that some uses must be sacrificed or diminished to maintain the quantity or quality of others (Alexander 1977). However, all areas cannot be managed for the same, or a single, resource or value at the detriment of other resources. Today, land managers are concerned with ecosystem sustainability implying they manage for all resources. This concept, and mandate, would imply an even further reduction in the percentage of “suitable and treatable” land base that could be dedicated to water yield augmentation at the detriment of other resources. Current revisions of the Forest Plans reflect these complex tradeoffs more so than past efforts.

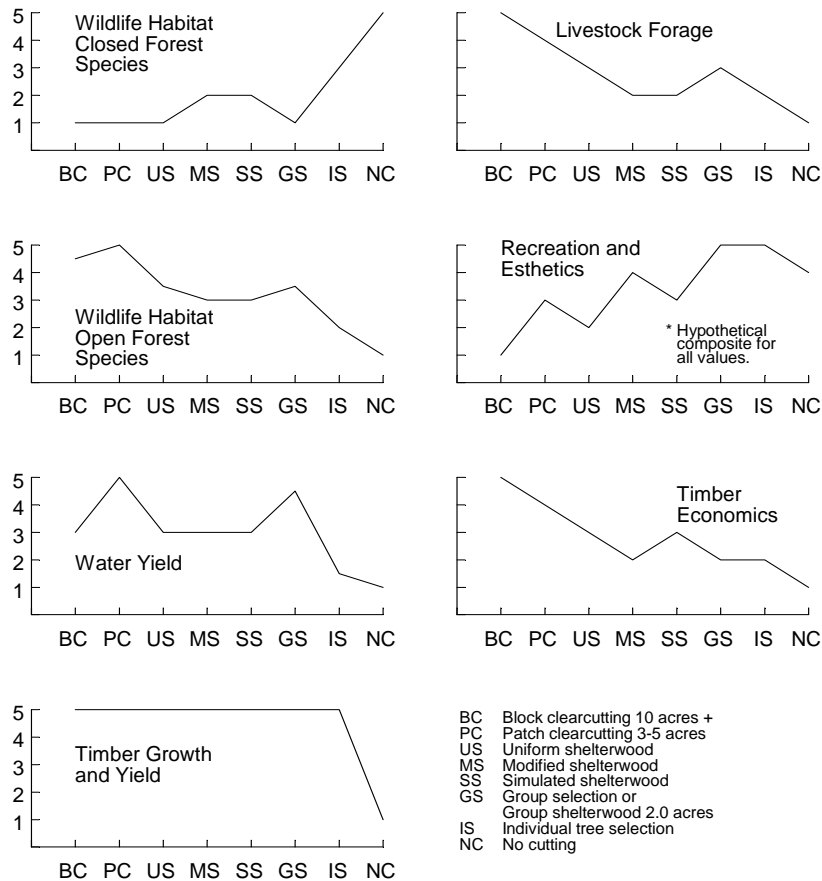


Figure 11. Relative ranking of the effects of cutting methods on the resources of spruce-fir forests. Scale: 1 signifies the least favorable, 5 the most favorable.

ANALYSIS

THE DATA BASE

Of primary concern to the analysis, especially with respect to the opportunity for water yield augmentation, is not the total number of acres of National Forest land in the North Platte drainage but the designated use, or management class, assigned to the acreage. Constraints associated with the management class designations dictate the availability, or suitability, of the land for timber harvest. Initial data provided by the Forest Service, R-2, indicated there are approximately 1,640,000 acres of land on the MB, RT, and AR National Forests that contribute flow directly to the North Platte River Basin. Scrutiny of the secondary delimiters associated with the polygon (stand or unit area) descriptions indicate that approximately 298,000 acres of the 1,640,000 total acres are not actually owned by the Forest Service. They were included in the initial estimate of the forest area because they represent an administrative site on the MBNF. Therefore, net Forest Service ownership in the North Platte River drainage is approximately 1,343,000 acres. As a point of reference, when discussing opportunity to detect changes in flow as a result of management practices on the 1,343,000 acres of NFS land, there are 19,776,000 acres in the drainage area of the North Platte River above North Platte, Nebraska; only seven percent of which is Forest Service owned.

Management Class

The 1,343,000 acres have been allocated to one of four different management classes, described as follows:

- 1) Wilderness – legally withdrawn from harvest.
- 2) Unsuitable for Harvest – those areas considered to be non-commercial, subject to irreversible damage, inoperable, not capable of being restocked in 5 years, not suitable for timber production (e.g. recreation areas, RNA's, etc.), and areas where adequate response data is not available.
- 3) Tentatively Suitable for Harvest - those areas where timber production is feasible but incompatible with current allocation.
- 4) Suitable for Timber Harvest – those areas presently suitable for timber harvest. This class may include areas already harvested, as well as non-commercial or non-stocked stands.

Designation of management classes were done by the respective Forest staffs, on each of the 3 National Forests. We did not question the definitions or the allocations as part of this effort. Allocations are assumed consistent with Forest Plan revisions and data resolution does not allow further characterization, or justification, of the allocations within each of the four management classes.

Of the total 1,343,000 acres of national forest land in the North Platte drainage, approximately 223,000 acres, or 16.5 percent of the total, is designated Wilderness. Approximately 391,000 acres, or 29 percent of the total, has been determined to be Unsuitable for Timber Harvest. Of the remaining 731,000 acres, 502,000 acres, or 37 percent of the total, is designated Suitable for Timber Harvest while the remaining 229,000 acres are considered Tentatively Suitable for Timber Harvest. The U.S. Forest Service management class designations define those areas available for timber harvest, and those, which are not available.

Stand Description

The information provided to us by the U.S. Forest Service was derived from the current (ca. December 1999) GIS database. In total, data consisted of characterizing approximately 23,000 separate polygons or unit areas. Each polygon represents an area with a matrix of descriptive parameters describing the area the polygon represents and the nature of the uniform cover type it represents. The descriptive parameters include aspect, elevation, 6th order watershed location, and cover type.

Cover Type

Each polygon portrays a single Cover Type that can be characterized as either water, barren, grass, shrub, or forest. Information on specie composition, basal area, cover density, and size class further characterize the forest cover type. No further information is given on the other cover types. Less than one percent of the total 1,343,000 acres of Forest Service ownership is covered by water (8303 acres). Barren Area designation occupies 2.75 percent of the total area or 36,971 acres, while grasses occupy 5.8 percent or 77,729 acres. Brush dominates on 112,000 acres or 8.4 percent of the total NFS lands. Because of the minimal acreage occupied by cottonwood, the 122 acres were added to the acreage designated as water or

“wet.” In total, 227,511 acres or 17 percent of the total Forest Service ownership is classified as non-forest. The balance of NFS lands, 1,107,593 acres or 83 percent of the total ownership, is cover typed as forestland.

Species composition on the forested land consists of 61,869 acres of aspen (5.6 percent of forested area), 12,257 acres of Douglas fir (1.1 percent of forested area), 11,546 acres of Limber pine (1.0 percent of forested area), 87,849 acres of ponderosa pine (7.9 percent of forested area), 306,000 acres of spruce-fir (27.6 percent of forested area). Lodgepole pine occupies 627,963 acres or 57 percent of the total forest area. Rocky Mountain Juniper occupies about 70 acres and will not be considered further in this analysis.

Average size class of the stand represented by the polygon further characterizes forest cover type. Size classes for each stand (polygon) consisted of N (non-stocked), E (seedlings 0.0-0.9" DBH), S (seedlings 1.0-4.9" DBH), M (saplings 5.0 –8.9" DBH), L (poles 9.0-15.9" DBH), and V (sawtimber 16" + DBH). For purposes of further analysis, some of the classes were combined and four general size class categories were retained 1) non-stocked (N), 2) seedlings (E + S), 3) poles (M), and 4) sawlogs (L + V). The lumping was necessary to coincide with the stand age data also provided by the Forest Service. Approximately one percent of all Forest Service land currently typed as forested is non-stocked (N), 10-11 percent is in the seedling stage (E+S), 30 percent is in the pole class, and the balance of over 55 percent is in the sawtimber class (L+V). However, only two percent of the total forested area is occupied by sawtimber stands that average 16" DBH and larger. The percentages are similar across all management classes (e.g. Wilderness, Suitable for Harvest, etc.).

Secondary Data

Age Distributions

In addition to the GIS-generated polygon data, file data from field surveys were also provided that describe average stand age by species for the four size classes. Initially, separate stand age data was provided by each of the three forests but regression analysis did not demonstrate significant differences in the age/size class relationships between forests, so the data were combined. Models were then fit to predict average basal area (Y) for each of the stand size classes, as a function of age (X) for each forest

species. The relationships for lodgepole pine, spruce-fir, and aspen, the three most prevalent species, are presented in figures 12a – 12c.

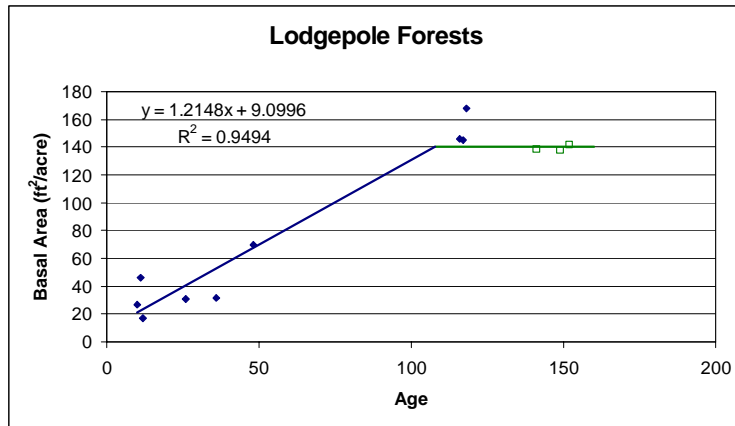


Figure 12a: Relationship between basal area (Y) and age (X) for Lodgepole Pine.

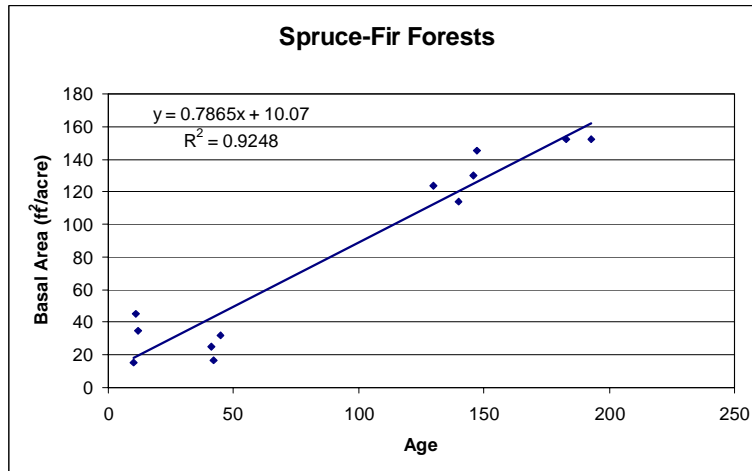


Figure 12b: Relationship between basal area (Y) and age (X) for Spruce-Fir.

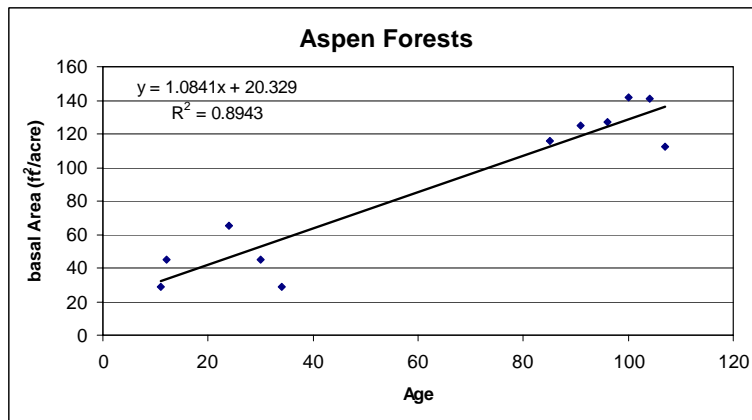


Figure 12c: Relationship between basal area (Y) and age (X) for Aspen.

Precipitation

Forest Service staff assisted us by superimposing the Oregon State University Climate Center Precipitation Map for Colorado and Wyoming on the DEM's for the respective Forests to estimate mean annual precipitation as a function of elevation for the polygons. Mean monthly precipitation data for a number of precipitation gauges in Colorado and Wyoming, were then used by us to estimate the percentage of annual precipitation occurring in each month, as a function of elevation (table 1). As a general observation, the amount of annual precipitation increases with elevation (about 20 percent increase per 1000 ft rise in elevation) while the percent of the annual precipitation (storms) that occurs in the summer months increases with decreasing elevation (table 1).

The percent of annual precipitation occurring in each month, table 1 was used to partition the estimates of annual precipitation, generated by the U.S. Forest Service from the GIS layers, into monthly values, for each of the elevation zones. Estimates of monthly precipitation are the required input for the electronic version of the WRENSS hydrologic model we used. However, the monthly values are in turn aggregated to the seasonal values stipulated as input in the original WRENSS procedure (Troendle and Leaf 1980).

Table 1. Percent of annual precipitation occurring in each month by elevation zone.

Elevation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5000	0.041	0.035	0.071	0.111	0.194	0.140	0.103	0.068	0.074	0.074	0.048	0.039
6000	0.045	0.053	0.077	0.119	0.170	0.124	0.098	0.073	0.073	0.078	0.064	0.048
7000	0.056	0.050	0.081	0.106	0.142	0.106	0.112	0.083	0.073	0.080	0.065	0.053
8000	0.092	0.071	0.098	0.107	0.100	0.072	0.073	0.064	0.070	0.069	0.088	0.098
9000	0.104	0.089	0.107	0.106	0.092	0.058	0.056	0.057	0.060	0.068	0.098	0.106
10000	0.105	0.093	0.110	0.123	0.103	0.054	0.052	0.046	0.058	0.070	0.092	0.097
*11000	0.105	0.093	0.110	0.123	0.103	0.054	0.052	0.046	0.058	0.070	0.092	0.097
*12000	0.105	0.093	0.110	0.123	0.103	0.054	0.052	0.046	0.058	0.070	0.092	0.097

*For observations over 11,000' use 10,000' values.

Summary of Data Set

Data provided to us, by the U.S. Forest Service, described approximately 23,000 polygons, or homogeneous units of area, that in aggregate represent the total U.S. Forest Service ownership in the North Platte River Basin. For each polygon, the management class, cover type (including: specie composition, size class, basal area, age, and cover density, when appropriate), aspect, and elevation, were provided. For each polygon, data are also available to estimate mean monthly precipitation. When simulating hydrologic response, the polygons, or unit areas, expressing similar characteristics were aggregated to reduce the number of computer runs. In anticipation of the alternatives that would be simulated, and the questions that might arise, we interrogated the distribution of the polygons with respect to certain characteristics. We found, for example, little difference exists in the percentage of U.S. Forest Service ownership that falls in the saw log size class, by management class. Wilderness areas do not appear to be any more dominated by larger (older) stands than areas designated as Suitable for Harvest. Although the largest polygons, or unit areas, are as large as 3000 acres, more than 95 percent of the total forested area, regardless of management class, is characterized by polygons less than 1 square mile, or 640 acres in size with the majority of the units less than 60 acres. Because of the relatively small size of the units, on-the-ground management opportunities will be influenced by the dispersal of the units as well as availability of access to them. The alternatives we will propose will not address that problem but experience with Coon Creek tells us that the real opportunity for timber harvest and therefore water yield augmentation will not be as great as anticipated or simulated. Appendix A presents the current database, less the annual precipitation data.

HISTORICAL TRENDS IN WATER YIELD

As noted earlier, there are currently 1,107,593 acres of forested land, owned by the U.S. Forest Service, in the North Platte River Basin. Species composition is predominantly lodgepole pine and spruce fir (table 2). There are significant amounts of ponderosa pine and aspen with lesser amounts of douglas fir and limber pine (table 2). Fifty-five percent of all stands are in the sawtimber class with the majority of the balance in the pole size class.

Ponderosa pine stands are almost entirely (91 percent) in the sawtimber class. (Acreages are truncated at the decimal point in all tables).

The data presented in table 2, describing current forest stand condition in the North Platte River Basin are consistent with the stand configuration data summary for Colorado and Wyoming presented in the USDA Forest Service 1997 RPA Assessment of the Nations Forests. (Draft tables dated 10/15/99). The draft RPA Assessment does not allow partitioning of the data with the specificity of table 2, but the spatial relationship between species and stand class appears consistent with the data in table 2.

Table 2: Area of Forest Cover by Specie and Size Class on National Forest Land in the North Platte River Basin -- Year 2000.

Species	Acres				
	Non-Stocked	Seedlings/ Saplings	Poles	Sawtimber	Total
Spruce-Fir	3,478	32,622	39,958	230,051	306,108
Lodgepole Pine	6,533	91,504	257,940	271,986	627,963
Ponderosa Pine	3,816	1,086	2,994	79,953	87,849
Douglas Fir	102	132	2,819	9,203	12,257
Limber Pine	24	303	6,594	4,625	11,546
Aspen	1,614	7,946	29,126	23,182	61,869
Total	15,567	133,593	339,430	619,002	1,107,593

Note: Spruce-Fir, Lodgepole, and Aspen have a high degree of younger stands (non-stocked and seedlings and saplings). Ponderosa pine, Douglas Fir, and Limber pine are more heavily weighted to pole and sawtimber classes.

Characterization of historical stand condition on National Forest land started with the current condition and worked backwards, in 20-year increments, to 1860.

Numerous assumptions were made in the assessment process. First, we assumed that the average age of the forest, by stand size class, was a reasonable estimate of mean age for that size class. Individual plot data provided by the U.S. Forest Service, indicated that individual trees within the stands could be much older, for example than the 150-year mean age for lodgepole pine sawtimber, as indicated in figure 12a. Personal communication with Dr. Wayne Shepperd (Research Silviculturalist, Rocky Mountain Research Station, Fort Collins, CO) supported our assumption. Stands in the North Platte River Basin have been impacted by natural disaster and human intervention more than many other places in Region 2,

thus resulting in what appear to be relatively young stands. Second, we assumed that as we subtracted 20-years from the current age of each stand, it remained in the same size class (and hydrologic condition) unless the new stand age fell below the midpoint in the range in years between the current size class and the next younger size class. Once past the mid-point between two age classes, the stand was moved to the next lower age class. If a size class was non-stocked, it was assumed that 20-years earlier it was a sawtimber stand and the pattern repeated. In this way, the current size classes were projected back in time, at 20-year intervals, to the year 1860. We did not account for stand evolution or changes in specie composition that might also have occurred over time. We also had to assume there was compatibility between the field survey derived estimates of stand age for the 4 classes and the GIS based estimates of area in each size class. Finally, it was assumed that the hydrologic model, WRENS, could be used to characterize the annual water yield for the forest conditions characterized at 20-year increments from 1860 to 2000.

Any trends in the water yields simulated for the forest condition assumed to exist at successive increments of time is assumed to reflect the effect of forest cover changes on water yield. This phase of the analysis was performed on all national forest forested land in the North Platte River Basin. The estimate of total acres in each of the 4 size classes for the period 1860 to 2000 is presented in table 3.

At first glance, the projections in table 3 seem erratic. For example, we can pretty well assume there were more than zero non-stocked acres in 1940 and that some sawtimber stands were present in 1920; contradicting the numbers presented in table 3. However, these discontinuities or discrepancies are a result of working with age class means, size class means, perhaps with the choice of a time increment, and with the assumption that one size class is reduced to its preceding size class at the mid-point in years between the two size classes. Discontinuity is a problem that occurs whenever discrete values are used to describe continuous, and often non-linear functions. The value of the information in table 3 is in the trends it expresses. Currently (year 2000) over 50 percent of the forested area is occupied by relatively young sawtimber stands that were quite young in 1860.

Table 3: Estimated Area (Acres) in the Four Major Size Classes for the Period 1860 to 2000.

Year	Size Class (Acres)				Total Forest Acres
	Non-Stocked	Seedlings/ Saplings	Poles	Sawtimber	
1860	397,930	378,594	297,357	33,712	1,107,593
1880	55,385	697,522	92,137	262,548	1,107,593
1900	285,731	654,913	156,462	10,488	1,107,593
1920	35,860	833,308	238,424	-	1,107,593
1940	-	365,292	709,189	33,111	1,107,593
1960	33,057	193,146	789,152	92,238	1,107,593
1980	133,461	132	952,339	21,661	1,107,593
2000	15,567	133,593	339,430	619,002	1,107,593

The water balance for current stand conditions was then simulated using WRENSS (Troendle and Leaf, 1980) modified to account for reductions in interception loss rather than redistribution, for stands reduced in density. Based on the research, referenced earlier an adjusted set of snow-pack modifier coefficients were used for lodgepole pine (figure 13), spruce-fir (figure 14), and aspen (figure 15). The function for aspen was derived from Rocky Mountain Research Station file data collected in numerous clear cuts and surrounding forest on Stoner Mesa in southern Colorado and from thinned aspen stands on the Fraser Experimental Forest. No adjustment in interception savings is made for aspect in aspen stands. The winter interception function for lodgepole pine and spruce-fir is that published by Troendle (1987) adjusted for aspect differences. The aspect adjustment represents a composite based on more recent research by Troendle, Schmidt, and others (Troendle 1987; Schmidt and Troendle 1989; Troendle *et al.* 1993; Troendle and Reuss 1997; Wheeler 1984; Meiman 1987). The winter precipitation was adjusted by the modifier coefficient appropriate to the residual basal area in the polygon, as a percentage of basal area maximum for the specie (100 percent on the x axis equals the basal area at complete hydrologic utilization). Basal area maximum for spruce-fir is $150 \text{ ft}^2\text{acre}^{-1}$ while it is $120 \text{ ft}^2\text{acre}^{-1}$ for lodgepole pine, and $110 \text{ ft}^2\text{acre}^{-1}$ for douglas fir, ponderosa pine, aspen, and limber pine. The historical water yield, simulated using WRENSS, along with the estimated area of each size class is presented in table 4 for each 20-year increment from 1860 to 2000. A bar graph (figure 16) presenting area, in acres, in each size class (Y_1) and water yield (Y_2) are plotted over year (x) for the 140-year period from 1860 to present. The bar graph demonstrates the general shift from a high degree of less developed stands in 1860 and the gradual progression to presumably denser sawtimber stands by the year 2000. The simulated reduction in

stream flow from almost 15 area inches in 1860 to 12 inches in 2000 is equally apparent. The most rapid decline in stream flow occurred from 1900 to 1940. Again, it should be noted that the critical observation is the trend that appears to have occurred. Tables 5 to 10 and figures 17 to 22 present similar information by individual forest specie: lodgepole pine, spruce-fir, ponderosa pine, douglas fir, limber pine and aspen. Note that ponderosa and limber pine as well as douglas fir were treated as mixed conifer and modeled using spruce-fir algorithms. Precipitation, aspect, elevation, and interception functions varied accordingly, however, for all species.

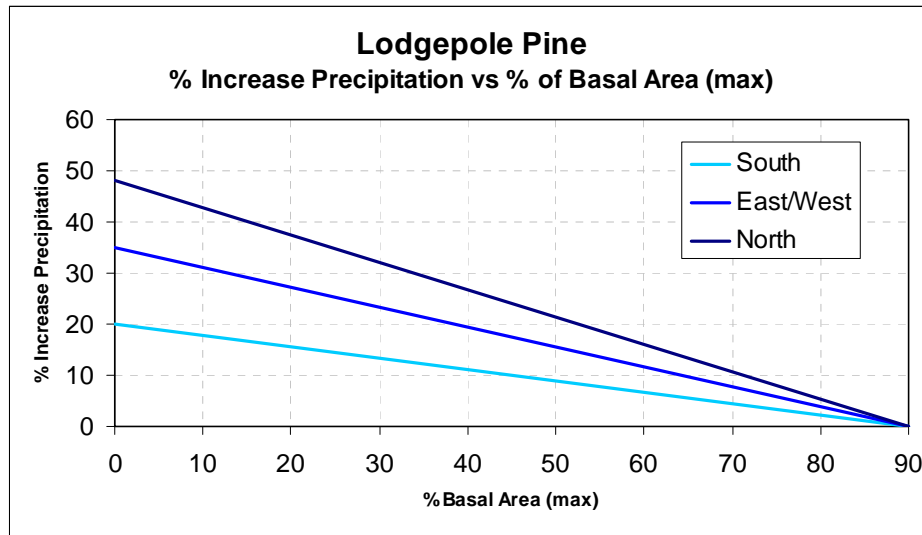


Figure 13: Relationship between the percent increase in precipitation (snow water content) and basal area, expressed as the maximum for complete hydrologic utilization for Lodgepole Pine.

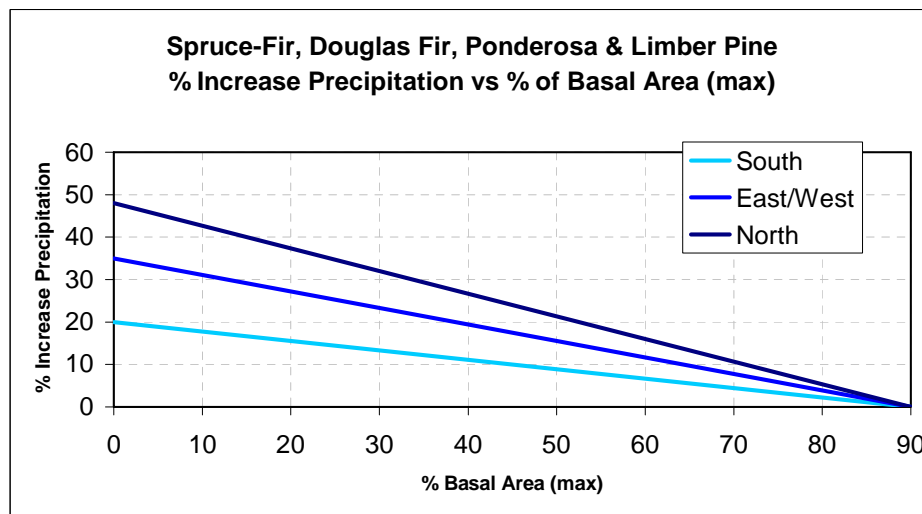


Figure 14: Relationship between the percent increase in precipitation (snow water content) and basal area, expressed as the maximum for complete hydrologic utilization for Spruce-Fir.

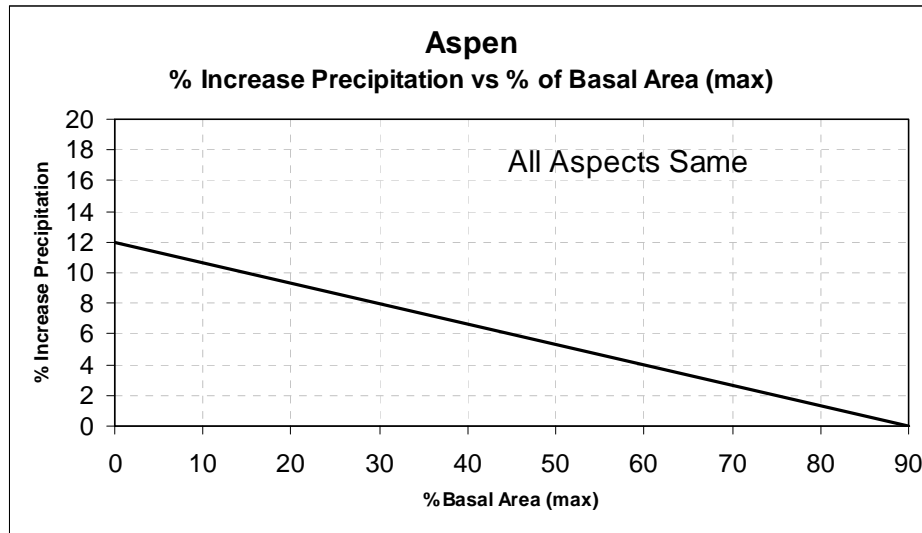


Figure 15: Relationship between the percent increase in precipitation (snow water content) and basal area, expressed as the maximum for complete hydrologic utilization for Aspen.

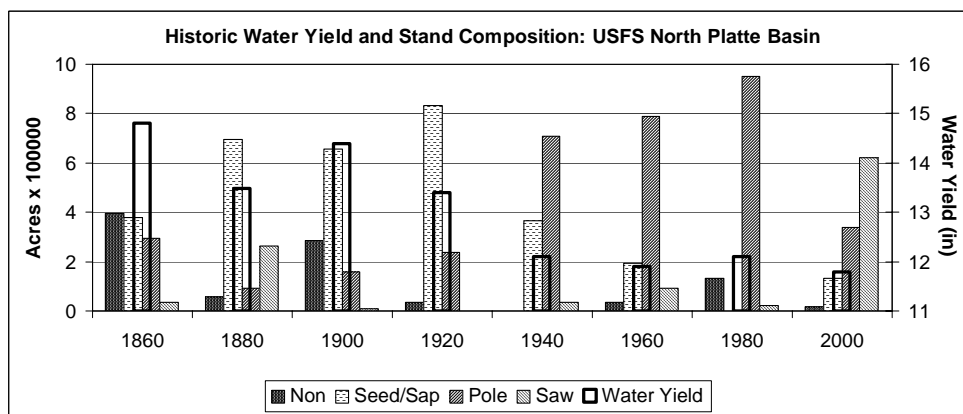


Figure 16: Historic water yield and stand composition, all species.

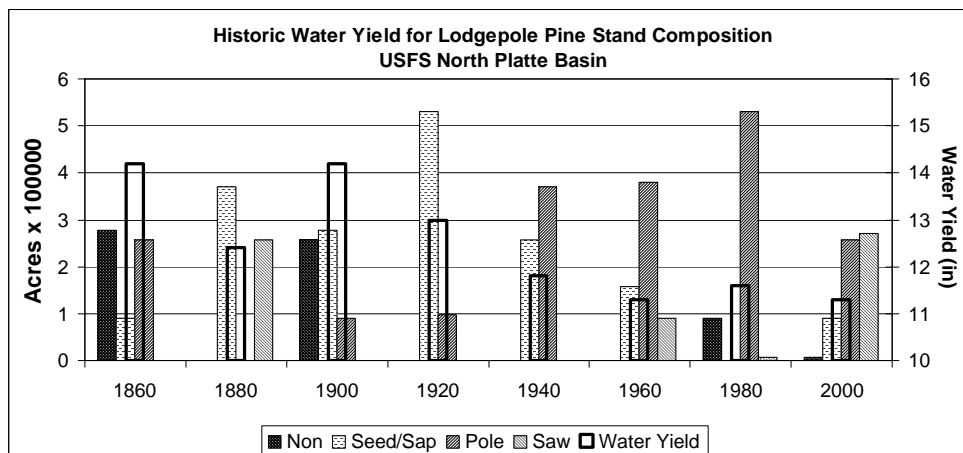


Figure 17: Historic water yield and stand composition, Lodgepole Pine.

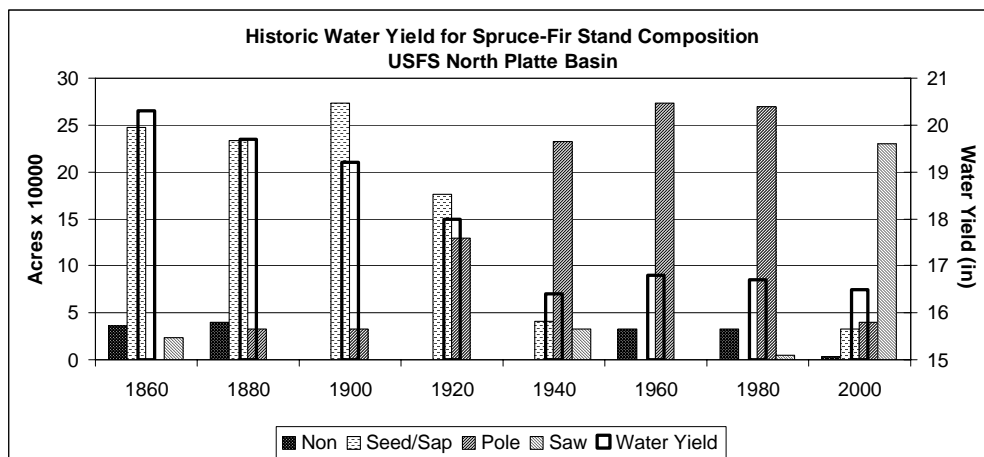


Figure 18: Historic water yield and stand composition, Spruce-Fir.

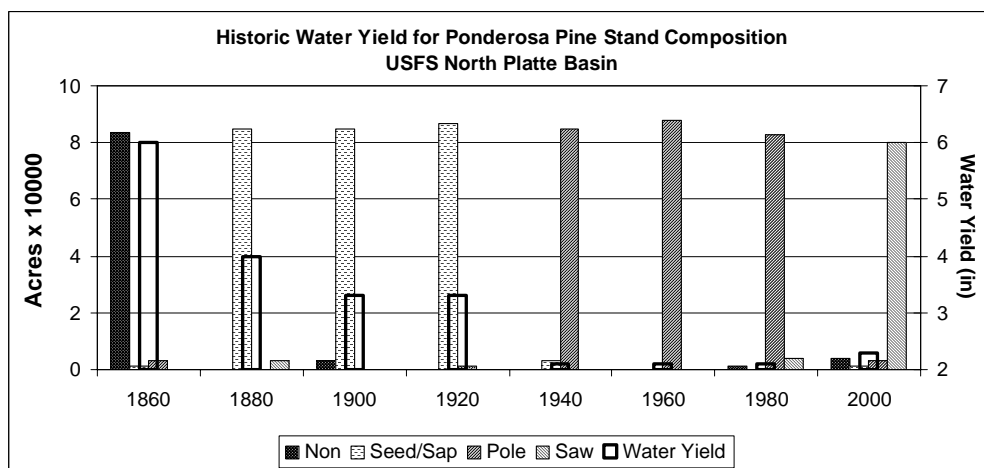


Figure 19: Historic water yield and stand composition, Ponderosa Pine.

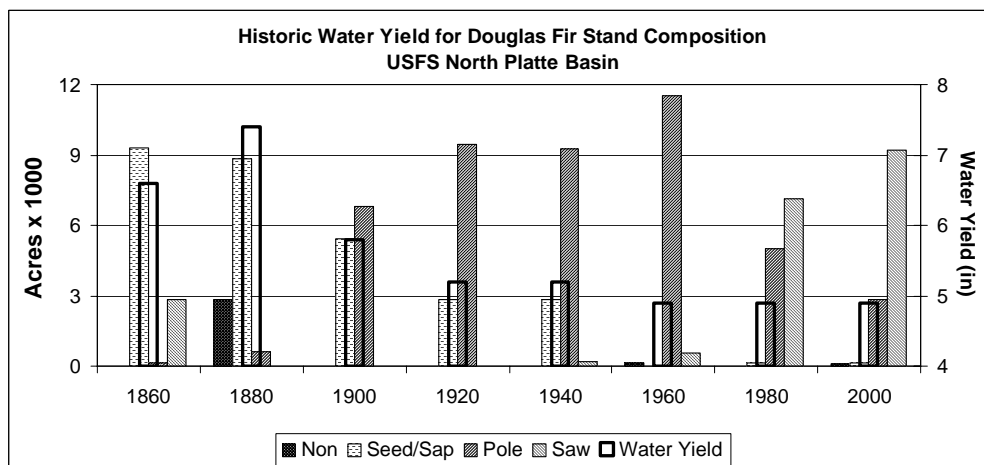


Figure 20: Historic water yield and stand composition, Douglas Fir.

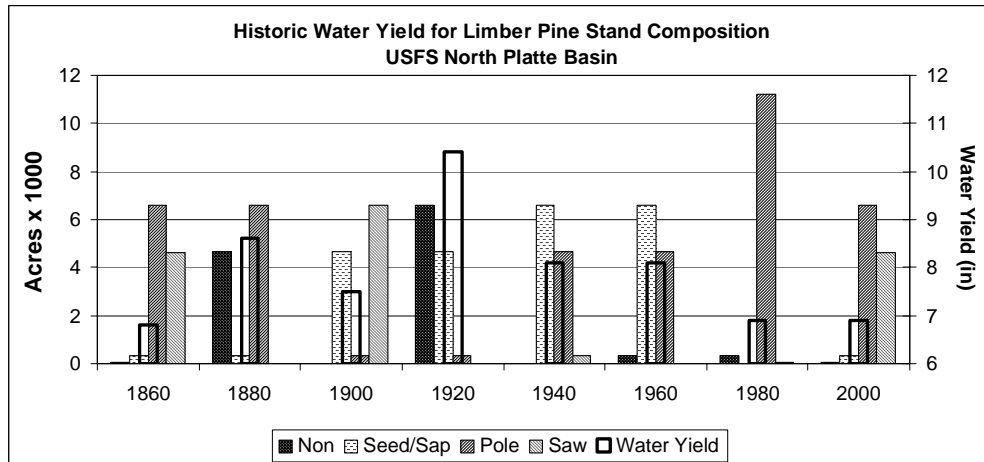


Figure 21: Historic water yield and stand composition, Limber Pine.

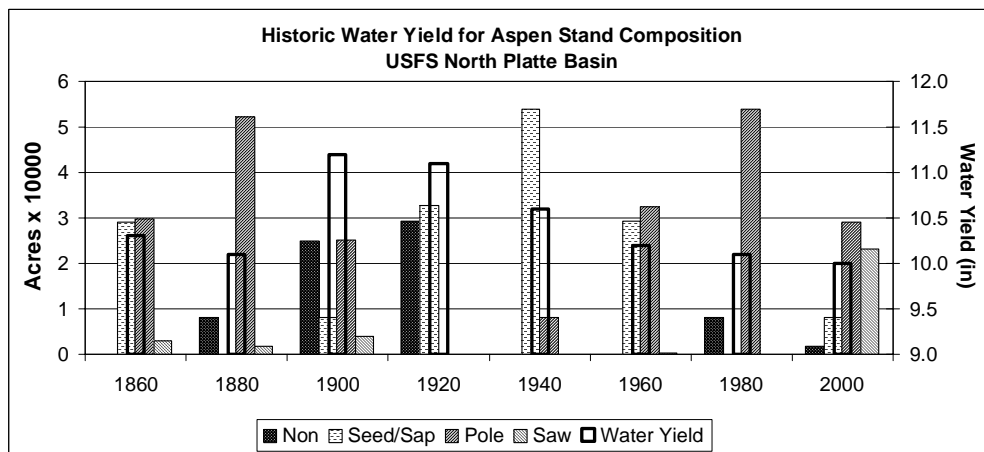


Figure 22: Historic water yield and stand composition, Aspen.

Table 4: Historical trend in stand composition and water yield, all species.

Date	Water Yield	Non-stocked	Seedling/Sapling	Pole	Sawtimber	Total
1860	14.8	397,930	378,594	297,357	33,712	1,107,593
1880	13.5	55,385	697,522	92,137	262,548	1,107,593
1900	14.4	285,731	654,913	156,462	10,488	1,107,593
1920	13.4	35,860	833,308	238,424		1,107,593
1940	12.1		365,292	709,189	33,111	1,107,593
1960	11.9	33,057	193,146	789,152	92,238	1,107,593
1980	12.1	133,461	132	952,339	21,661	1,107,593
2000	11.8	015,567	133,593	339,430	619,002	1,107,593

Table 5: Historical trend in stand composition and water yield, Lodgepole Pine.

Acres Lodgepole Pine by Size and Year						
Date	Water Yield	Non-stocked	Seedling/Sapling	Pole	Sawtimber	Total
1860	14.2	278,519	91,503	257,940		627,963
1880	12.4	13	370,009		257,940	627,963
1900	14.2	257,940	278,520	91,503		627,963
1920	13.0		529,926	98,036		627,963
1940	11.8		257,940	370,023		627,963
1960	11.3		157,035	379,423	91,503	627,963
1980	11.6	91,503		529,926	6,532	627,963
2000	11.3	6,532	91,503	257,940	271,986	627,963

Table 6: Historical trend in stand composition and water yield, Spruce-Fir.

Acres Spruce-Fir by Size and Year						
Date	Water Yield	Non-stocked	Seedling/Sapling	Pole	Sawtimber	Total
1860	20.3	35,617	247,269	0	23,222	306,108
1880	19.7	39,958	233,528	32,621		306,108
1900	19.2		273,486	32,621		306,108
1920	18.0		176,548	129,560		306,108
1940	16.4		41,023	232,463	32,621	306,108
1960	16.8	32,621	250	273,236		306,108
1980	16.7	32,621		269,333	4,153	306,108
2000	16.5	3,477	32,621	39,958	230,051	306,108

Table 7: Historical trend in stand composition and water yield, Ponderosa Pine.

Acres Ponderosa Pine by Size and Year						
Date	Water Yield	Non-stocked	Seedling/Sapling	Pole	Sawtimber	Total
1860	6.0	83,769	1,086	2,994		87,849
1880	4.0		84,856		2,994	87,849
1900	3.3	2,994	84,856			87,849
1920	3.3		86,763	1,086		87,849
1940	2.1		2,994	84,856		87,849
1960	2.1			87,849		87,849
1980	2.1	1,086		82,947	3,816	87,849
2000	2.3	3,816	1,086	2,994	79,953	87,849

Table 8: Historical trend in stand composition and water yield, Douglas Fir.

Acres Douglas Fir by Size and Year

Date	Water Yield	Non-stocked	Seedling/Sapling	Pole	Sawtimber	Total
1860	6.6		9,306	131	2,818	12,257
1880	7.4	2,818	8,824	613		12,257
1900	5.8		5,455	6,801		12,257
1920	5.2		2,818	9,438		12,257
1940	5.2		2,818	9,251	186	12,257
1960	4.9	131		11,540	584	12,257
1980	4.9		132	4,990	7,134	12,257
2000	4.9	102	131	2,818	9,203	12,257

Table 9: Historical trend in stand composition and water yield, Limber Pine.

Acres Limber Pine by Size and Year

Date	Water Yield	Non	Seed/Sap	Pole	Saw	Total
1860	6.8	24	303	6,594	4,624	11,546
1880	8.6	4,648	303	6,594		11,546
1900	7.5		4,648	303	6,594	11,546
1920	10.4	6,594	4,648	303		11,546
1940	8.1		6,594	4,648	303	11,546
1960	8.1	303	6,594	4,648		11,546
1980	6.9	303		11,218	24	11,546
2000	6.9	24	303	6,594	4,624	11,546

Table 10: Historical trend in stand composition and water yield, Aspen.

Acres Aspen by Size and Year

Date	Water Yield	Non	Seed/Sap	Pole	Saw	Total
1860	10.3		29,125	29,696	3,046	61,869
1880	10.1	7,946		52,307	1,614	61,869
1900	11.2	24,796	7,946	25,232	3,893	61,869
1920	11.1	29,265	32,602			61,869
1940	10.6		53,922	7,946		61,869
1960	10.2		29,265	32,452	150	61,869
1980	10.1	7,946		53,922		61,869
2000	10.0	1,614	7,946	29,125	23,182	61,869

Overall, based on the range in simulated response, water yield has decreased almost 20 percent, or 3 area inches since 1860. This equates to a decrease in flow of nearly 225,000 acre-feet of water from 1.3 million acres of National Forest lands in the North Platte River Basin. The greatest reduction in flow occurred in spruce-fir stands (3.8 inches or an 18 percent reduction) and the smallest reduction occurred in limber pine. Ponderosa pine (table 7) exhibited the largest initial decline (1860 to 1900) with more moderate decreases since then. Given the precipitation regime estimated for each of the species, the current estimates of stream flow seem reasonable for lodgepole pine, spruce-fir, the forest types for which we have the most stream flow data and experience. The historical change in flow, based on the estimates of forest cover changes over time, also seems reasonable relative to the referenced watershed experiments expressing similar changes in cover density. It is difficult to say if the 20 percent change in flow, over a 140-year period, would be detectable at an off-site streamgage. Perhaps it would be at the forest boundary but less likely at a downstream streamgage.

In evaluating the historical trends in water yield, as presented in table 4, several factors should be considered. There is a “lot” of fluctuation in yield from 1860 – 1900 that reflects the fluctuations in stand configuration mentioned earlier. Because of the fluctuations in periodic responses, one should average the flow simulated for the 1860 - 1900 period at 14 or 14.1 inches. At the same time, the flow for the period from 1940 to present is fairly uniform at 11.9 to 12.0 inches. Averaging flow for the 2 time periods would indicate a 2.0 area inch decrease in flow occurred from 1860 to present resulting in an 185,000 acre-foot decrease in water yield. The latter estimate is a more conservative but perhaps more realistic estimate of the reduction in flow that might have occurred as a result of forest growth. This decrease in flow is still quite large relative to total yield. Individual specie responses are very consistent with how we would expect those species to respond ecologically and hydrologically over time.

OPPORTUNITY TO INCREASE WATER YIELD FROM THE NORTH PLATTE RIVER BASIN

Evaluation of the trends in water yield as a result of the historical changes in stand structure and vegetation density was based on all NFS lands in the North Platte drainage that are currently occupied by forest. Nothing was assumed to have changed with respect to water, barren, grass or brush lands. An evaluation of the current opportunities to increase water yield, through

forest management, can only be done on that portion of NFS forestlands considered Suitable for Timber Harvest. In total, there are currently 502,000 acres of NFS land considered suitable for timber harvest. Of the 502,000 acres, 71 percent or 355,354 acres are lodgepole pine dominated. Spruce-Fir represents 25 percent, or 124,281 acres of the balance. The remaining 4 percent of the suitable acreage consists of ponderosa pine (14,179 acres), aspen (7,278 acres), douglas fir (764 acres), and limber pine (118 acres). Although insignificant in the water yield alternatives, the area in limber pine and douglas fir was lumped with ponderosa pine and managed similarly.

Of the total 1,107,593 acres of NFS forested land in the North Platte River Basin, 273,947 acres or 25 percent of the total is in the Laramie River drainage. Of the 501,974 acres of NFS land suitable for timber harvest, 94,143 acres or 18 percent resides in the Laramie River drainage. Size class distribution is similar in both drainages but precipitation is lower in the Laramie River and the simulated water yield for current forest condition is less than that for the balance of the North Platte (7.8 inches versus 13.1 inches).

The lodgepole pine type is by far the most common forest cover on the NFS lands. The preferred management alternative for lodgepole pine, a pioneer species, is even aged silviculture. Historically regenerated by fire, clear cutting is used to regenerate the stand mechanically. Lodgepole will be managed on a 120-year rotation (personal communication, Dr. Wayne Shepperd, Rocky Mountain Research Station) and the intent is to emulate natural disturbance such as fire in selecting the harvesting pattern. Clear cuts would be relatively small (5-10 tree heights in width) and irregularly shaped in a manner similar to the treatment applied to Coon Creek on the MBNF (Troendle *et al.* 1998). Large clear cuts, several hundred acres in size, could be created through mechanical means or using fire if they were irregularly shaped and contained adequate roughness to rise above and retain the winter snow pack (Troendle and Meiman, 1984, Troendle and Bevenger, 1995). The proposed alternative for lodgepole pine requires an annual harvest of 120th of the total area in lodgepole pine with the older (sawtimber) stands harvested first. Given that over 50 percent of the lodgepole type is currently in the sawtimber (greater than 9.9 inch DBH) class, harvesting should be sustainable for the entire 120-year rotation.

The baseline simulation of water yield from the lodgepole pine stands that are classed as Suitable for Timber Harvest indicates 11.1 inches of water is

currently being generated. Simulation of harvesting 1:120th of the area in the year 2001 does not indicate any change in flow (rounding error) occurs. By the end of year 2005, when 5:120th are harvested, total flow would increase to 11.4 inches (or a 0.3 inch increase in water yield from the entire over 355,354 acres of lodgepole pine). By 2015, when 15:120th of the area would be harvested, simulated flow increased to 12.0 inches reflecting a 0.9 inch increase over the 15-year period. This equates to an increase of 26,651 acre-feet of water per year in year 2015. It would be at this point in time that as we proceed in the harvesting alternative we would also begin to simulate a decrease in flow or hydrologic recovery from the area harvested in 2001. The hydrologic recovery period can be expected to take a total of 60 to 70 years (Troendle and King 1987), so the efficiency of additional cutting in subsequent years beyond 2015 would continue to exceed declines due to re-growth in earlier harvest areas, for many years; perhaps 50 years. Increases in flow should eventually reach and sustain 40,000 acre-feet of water per year from lodgepole pine throughout the rotation. It would be possible to accelerate the harvesting and generate greater water yields at least in the near term, because over 50 percent of the lodgepole cover type is in sawtimber class. However, an accelerated production rate now would not be sustainable either in terms of timber production or water yield over the long term.

Like lodgepole pine, aspen is also best managed using even aged management and like lodgepole pine, clear cutting on a 120-year rotation was the silvicultural tool simulated. There are currently 7,278 acres of aspen considered suitable for timber harvest. WRENS simulations indicate 13.3 inches of water is being generated from that cover type at present. Clear cutting 1:120th of the area (61 acres) did not alter flow in year 2001. By year 2005, 303 acres had been harvested yielding a 0.4 inch increase in flow. By year 2015, 915 acres had been harvested, yielding an additional 1.2 inches of water for a total increase in yield of 725 acre-feet of water per year. Depending on site quality and initial stocking (sprouting) density, aspen can recover hydrologically in anywhere from 15 to 45 years. This estimate is based on unpublished simulations of growth response, using GENGYM (Edminster 1978) and assuming complete hydrologic recovery occurs at a leaf area index of 5.25 (Troendle and Leaf 1980). If we assume an average 30-year recovery; the increase in flow from aspen can be sustained at about 1000 acre-feet per year over the 120-year rotation.

The balance of the conifer stands suitable for timber harvest were managed as uneven aged. Again, the management is on a 120-year rotation using partial cutting or individual and group selection as the harvesting method. The intention is to enter each sawtimber stand on a 30-year entry cycle, reducing the stand basal area to about $80 \text{ ft}^2 \text{ acre}^{-1}$ at each entry. Depending on the species, initial stand density varies up to $150 \text{ ft}^2 \text{ acre}^{-1}$. Each year 1:30th of the total area is thinned.

Spruce-Fir is the second most prevalent forest cover type in the North Platte drainage, occupying about 25 percent of NFS land or 124,281 acres. Approximately 4,143 acres of spruce-fir were thinned in 2001 with no change in flow simulated. After 5 years, a total of 20,714 acres were harvested and water yield increased from 15.7 to 16.0 inches. After 15 years, 62,142 acres were harvested and flow increased to 16.6 inches. In total, the 0.9 inch increase in flow generated 9321 acre-feet of additional water per year. We expect the long-term sustainable increase over the 120-year rotation will average 14,000 acre-feet of water per year. This represents a sizable increase from the 124,281 acres of spruce-fir forest.

Ponderosa pine occupies 14,179 acres of the Suitable for Timber Harvest area. Ponderosa pine was also partially or selectively harvested and reduced to a basal area of $80 \text{ ft}^2 \text{ acre}^{-1}$. In the year 2001, 473 acres were partially cut with not impact on the base line water yield of 1.2 inches. By year 2005, 2363 acres of ponderosa pine were harvested with no simulated change in flow. Although minor increases in flow might be expected, precipitation was so limiting in this forest type that an increase in flow from timber harvest was not simulated.

Limber pine occupies only 118 acres of suitable area and hydrologic simulation indicated we could increase water yield from current yield of 8.6 inches in year 2000 to 9.5 inches in year 2015. Unfortunately, because of limited area, this equates to an increase in total yield of less than 10 acre-feet.

Douglas fir occupies only 764 acres of the Suitable for Timber Harvest area. Like limber pine, the area is too limited to generate much of a change. After 15 years of partial cutting, water yield increased from 12.0 inches to 12.6 inches and represents an increase of 38 acre-feet of water per year. Base water yield for douglas fir as presented in table 11 is much higher than the average water yield presented in table 8 for current conditions. This is a

reflection of a higher average precipitation on the acres Suitable for Timber Harvest than for the cover type as a whole.

Table 11 presents a summary of the water yield increases by period, for each of the forest types. Based on the data in Table 11, one can assume that managing the 502,000 acres of NFS land on a 120-year rotation, using a silvicultural alternative most appropriate to each forest type; additional 37,000 acre-feet of water could be realized by the year 2015. Maintaining the proposed rotations could result in a sustainable increase in water yield of 50 to 55,000 acre-feet of water per year by mid-rotation. Increases or decreases in the area considered Suitable for Harvest would result in a proportional increase or decrease in the potential flow change. The long-term potential increase equates to 0.11 acre-feet of water, or 1.3 inches, per acre of Suitable land. If, for example, the 227,000 acres of NFS land currently considered Tentatively Suitable for Harvest were included in the management rotation, another 16,000 acre-feet of water could be realized by year 2015.

The estimate of 50 – 55,000 acre-feet of water represents the increase in flow that we estimate can be attained through reasonable and prudent management. However, at least 12 percent of all NFS forested lands are below complete hydrologic utilization and these will continue to deplete the water resource as they mature. In the near term (next 30-50 years) the simulated increases will be offset, somewhat, by recovery in the younger, existing stands.

Table 11: Potential increases in flow on the North Platte River Basin resulting from timber harvest.

Specie	Base Water Yield in Inches	Water Yield Increase in Inches			Average Increase Per Year in 2015 (ft acre ⁻¹)
		2001	2005	2015	
Lodgepole Pine	11.1	11.1	11.4	12.0	26,650
Spruce-Fir	15.7	15.7	16.0	16.6	9,321
Aspen	13.3	13.3	13.7	14.5	727
Ponderosa Pine	1.2	1.2	1.2	1.2 ⁺	0
Limber Pine	8.6	8.5	8.9	9.5	7
Douglas Fir	12.0	12.0	12.2	12.6	38
TOTAL					36,743

THE POTENTIAL IMPACT OF CATASTROPHIC EVENTS ON WATER YIELD

There is concern that a spruce beetle outbreak could reach epidemic proportions as a result of the recent Routt blow down. The proximity of the potential outbreak area and the spruce-fir stands in the North Platte River Basin put those stands at risk as well. We simulated the short-term hydrologic consequence (10 year) of an outbreak in which 50 percent of the Spruce basal area in sawtimber stands and 30 percent of the spruce basal area in pole sized stands were killed by the beetle. All acres of spruce-fir were considered subject to impact, regardless of management class, as it would be unreasonable to assume that Wilderness or lands Not Suitable for Harvest would be spared.

The baseline hydrologic simulation for year 2000, presented earlier, indicated that annual water yield averaged 16.5 area inches for all stands in the spruce-fir type. Average basal area in the sawtimber stands is currently $149 \text{ ft}^2 \text{ acre}^{-1}$ while the pole stands average $127 \text{ ft}^2 \text{ acre}^{-1}$, both of which are at nearly complete hydrologic utilization.

We simulated the impact of the beetle killing 50 percent of the sawtimber and 30 percent of the pole-sized trees. Mortality was simulated to have occurred uniformly over a 10-year period (2001 – 2010). In year 1, or 2001, water yield increased from 16.5 to 16.6 inches. By year 10, water yield increased to 18.8 inches from the 306,000 acre spruce-fir type. The 2.2 inch increase is consistent with the increase of 2.0 inches Love (1955) observed following a budworm infestation on the White River in which 30 percent of the entire stand was killed. The 2.2 inch increase in year 2010 represents a 56,100 acre-foot increase in water yield per year. The increase in flow could persist, at a decaying rate, for as long as 60-70 years.

A second hypothetical simulation addressed the effect of fire in the lodgepole pine and ponderosa pine Forest types on water yield. The simulation assessed burning 30,000 acres. In this scenario, the 30,000 acre fire consumed 26,000 acres of lodgepole pine and 4,000 acres of ponderosa pine. An assumption was made that the fire would reduce “effective” basal area to 10 percent of its original value for the stands involved. As a result of burning 26,000 of the 627,963 acres of lodgepole pine, a 0.3 inch (11.3 to 11.6 inches) increase in flow, or 15,700 acre-foot increase in water yield was simulated. For ponderosa pine, burning 4,000 acres resulted in a 0.2 inch

increase, or a 1,464 acre ft increase in water yield. The water yield increase associated with burning (or clear cutting) ponderosa pine is much greater than that which can be attained by partially cutting, as in the earlier example of partial cutting. Water is severely limiting at the elevation the ponderosa pine normally occurs and residual vegetation utilizes any savings from partial cutting. In the Black Hills, where ponderosa pine occurs under wetter conditions, partial cutting can result in increased flow (Troendle and King 1987).

Because ponderosa pine occurs at lower elevations and in a drier precipitation regime, there is less opportunity to increase water yield. However, the lower elevations are subject to higher intensity rainfall events and storm flow following fire could increase significantly from the ponderosa pine type. Elevated storm response from the higher elevation spruce-fir type is less likely to occur (Troendle and Bevenger 1995).

“What if” simulations whether addressing beetle infestation or wild fire are intended to show the potential influence of massive vegetation removal on water yield that may well have occurred in the past, naturally. The simulated increase in flow following the Spruce beetle infestation yielded a result similar to that observed by Love (1955) following an infestation in the White River. The increase in flow from lodgepole pine following fire appears, at first, to exceed the 5.1 inch increase estimated to have occurred from Jones Creek following the greater Yellowstone fires of 1988 (Troendle and Bevenger, 1995). However, after accounting for talus slopes, alpine areas, and other open areas, Troendle and Bevenger (1995) concluded that the “effective” forest area burned on Jones Creek occupied only 55-60 percent of the total watershed area prior to the fire. In the fire simulation, it was assumed that the stand classes burned were in proportion to those present on the landscape. Over 80 percent of the lodgepole type is in the Pole and Sawtimber classes, at or near complete hydrologic utilization, so the 7.2 inch increase simulated to have occurred from the burned area, when only 10 percent of the basal areas is assumed to survive, seems reasonable and proportional to what was observed after the Yellowstone fire.

SUMMARY

Several issues stand out as a result of this analysis. First, and perhaps most interesting is the magnitude of the simulated decrease in flow that has occurred over the last 140 years; a decrease of 185,000 acre-feet or more of

water from 1,107,000 acres of NFS land. This estimate is greater than that estimated to have occurred using existing stream flow records (Leaf 1999).

Water yield from NFS lands on the North Platte is in general quite high because of the high precipitation input. Although the percentage of forestland Suitable for Timber Harvest is less than 50 percent of the total NFS lands, sizable increases in flow appear feasible using the 120-year rotation and appropriate silvicultural techniques for the specie.

In general, the simulated trends in stream flow whether the result of in-growth, harvesting, or catastrophe appear consistent with observed changes measured at the streamgage for treatments with a comparable impact. The hydrologic model WRENSS appeared to perform well when simulating the effects of fire, insect mortality, and timber harvest. Simulations of hydrologic response to both clear cutting and partial cutting compare well with observed changes in flow measured at the stream gauge, for similar impacts.

It would seem unlikely that the simulated changes in flow following timber harvest simulations would be detectable at any streamgage on the North Platte River. Neither is it likely that the simulated increases in flow could actually be detected as they exit NFS land, assuming a gauge were present to monitor them.

It is conceivable that decreases in flow on the order of magnitude simulated for the historical trend in forest cover could be detected downstream at a USGS gauge, if the gauge had an adequately long and consistent record. Since most gauges (North Platte at Northgate and Mitchell, North Platte below Whalen, etc.) were not initiated until the early 1900's, thus making detection of the flow reduction, as simulated, questionable.

We chose not to simulate the potential response to other management scenarios as part of this effort but the reality is, instead, that the outcome of virtually any scenario can be inferred from the range of scenario's we did simulate. For example, one can infer the relative impact of adding or subtracting Suitable acres based on simulated responses for the acreage currently available. One can also infer the impact of fully or partially implementing the management alternatives or a modification of them. Costs, in terms of water yield, can also be calculated as opportunity forgone for exclusions for Wilderness, wildlife set asides, and so on. To the degree the

data set provided to us properly characterizes the vegetation, the historical trend simulations are indicative of the cost, in water, of allowing vegetation density to increase. Although we did not specifically address peak flows and low flows, we would expect the nature of the simulated responses to fall within the frequencies and distributions observed on experimental watersheds. Except following fire at lower elevations (5 – 7,000 feet), we would not expect peaks or low flows to be altered.

In a very simple empirical model, (Troendle and Reusse, 1997) found that ET in the Sub alpine zone is equal to 18.1 inches of water plus 28 percent of all precipitation in excess of 18.1 inches. Forest removal (equivalent clear cutting) reduces that consumptive loss by almost 50 percent. Increasing forest vegetation adds consumptive use or increases, ET, following the same model. Vegetation manipulation, up or down, has tremendous potential for increasing or decreasing water yield as demonstrated by the scenarios simulated in this analysis and by the research and observational data that represents the foundation for the models used.

Acknowledgements

We would like to thank Skip Underwood and Mel Mehl, U.S. Forest Service, for their assistance and support in providing the data necessary for this analysis. A special thanks goes to Steve Williams, U.S. Forest Service, MBRTNF for his dedication in providing the data set.

Literature Cited

- Alexander, Robert R. 1977. Cutting Methods in Relation to Resource Use in Central Rocky Mountain Spruce-Fir Forests. *Journal of Forestry*. 75 (July): 395-400.
- Anderson, Henry W. 1955. Detecting hydrologic effects of changes in watershed conditions by double-mass analysis. *Trans of the Am Geo Union*, 36(1): 119-25.
- Bates, C. G. and A. J. Henry. 1928. Forest and stream flow experiment at Wagon Wheel Gap, Colorado. *U.S. Monthly Weather Review*, Supplement 30. Washington D.C. 79 p.

- Bevenger, G. S. and C. A. Troendle. 1987. The Coon Creek Water Yield Augmentation Pilot Project. In: Proc. Management of Sub alpine Forests: Building on 50 Years of Research, July 79, 1988, Silver Creek, Colorado. USDA Forest Service, Gen Tech. Rep., RM-149: 145-149.
- Bosch, J. M. and J. D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J of Hydrology. 55: 2-23.
- Burton, Timothy A. 1997. Effects of basin-scale timber harvest on water yield and peak stream flow. JAWRA. 33(6): 1187-1194.
- Callaham, R. Z. (Ed.) 1990. Case studies of watershed projects in Western provinces and States. Report 22. Wild Land Resource Center. University of California, Berkeley.
- Dietrich, T. L. and J. R. Meiman. 1974. Hydrologic Effects of Patch Cutting of Lodgepole Pine. Hydrology. Colorado State University, Fort Collins, CO. 31 p.
- Douglass, J. E. 1983. The potential for water yield augmentation from forest management in the eastern United States. Water Resource Bulletin. 19(3): 351-358.
- Edminster, Carleton B. 1978. RMYLD: Computation of yield tables for even-aged and two-storied stands. USDA Forest Service Research Paper RM-199. Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO 26 p.
- Garstka, W.U.; L.D. Love; B.C. Goodell; F.A. Bertle 1958. Factors affecting snowmelt and stream flow. Washington DC: U.S. Department of Interior, Bureau of Reclamation; U.S. Department of Agriculture, Forest Service; 189 p.
- Gary, Howard, L. and Charles A. Troendle 1982. Snow accumulation and melt under various stand densities in lodgepole pine in Wyoming and Colorado. Res. Note RM-417. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 7 p.

- Gary, H. L. and R.K. Watkins 1985. Snow pack accumulation before and after thinning a dog-hair stand of lodgepole pine. Res. Note RM-450. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 4 p.
- Harr, R. D. 1983 Potential for augmenting water yield through forest practices in western Washington and western Oregon. Water Resource Bulletin. 19(3): 383-393.
- Hoover, M. D. and C.F. Leaf 1967. Process and significance of interception in Colorado sub alpine forest. In: W. E. Sopper and H. W. Lull (Editors) Forest Hydrology. Pergamon, New York, N.Y. PP. 213-224.
- Hydrosphere, 1998. Hydrodata, Volume 10. USGS Daily Flow Values. Hydrosphere Data Products, Inc. Boulder, CO. Disk West-I.
- Kattleman, R. C., N. H. Berg, and J. Rector. 1983. The potential for increasing stream flow from Sierra Nevada watersheds. Water Resource Bulletin. 19(3): 395-401.
- Kircher, James E., Anne F. Choquette, and Brian D. Rickter. 1985. U. S. Geological Survey, Water Resources Investigations Report 85-4086. Lakewood, CO. 28 p.
- Leaf, Charles F. 1975. Watershed management in the Rocky Mountain sub alpine zone: the status of our knowledge. Res. Pap. RM-137. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 31 p.
- Leaf, Charles F. 1999. Cumulative Hydrologic Impacts of U.S. Forest Service Management Practices on the Routt, Arapaho-Roosevelt, Pike, and Medicine Bow National Forests: Potential for Water Yield Improvement. Platte River Hydrologic Research Center. Research Paper PRHRC-3. 15 p.
- Leaf, Charles F. and Robert R. Alexander. 1975. Simulating timber yields and hydrologic impacts resulting from timber harvest on sub alpine watersheds. USDA Forest Service Research Paper RM-133. Rocky

- Mountain Forest and Range Experiment Station, Fort Collins, CO. 20 p.
- Leaf, C. F. and G. E. Brink. 1973. Hydrologic simulation model of Colorado sub alpine forest. U.S. Dep. Agric. For. Serv. Res. Pap. RM-107, Rocky Mount. For. And Range Exp. Stn., Fort Collins, CO. 23 p.
- Love, L. D. 1955. The effect on stream flow of the killing of spruce and pine by the Englemann spruce beetle. Trans of the Am Geo Union. 36(1): 113-118.
- Meiman, James R. 1987. Influence of forests on snow pack accumulation. In: Management of Sub alpine Forests: Building on Fifty Years of Research. Proceeding of a Technical Conference, Silver Creek, Colorado, July 6-9, 1987. US For Serv Gen Tech Rep RM-149. 61-67.
- Ponce, Stanley L. Ed., 1983. The Potential for Water Yield Augmentation Through Forest and Range Management. American Water Resources Association. Water Resources Bulletin 19(3): 351-419.
- Ponce, Stanley L. and James R. Meiman. 1983. Water Yield Augmentation through Forest and Range Management, Issues for the Future. Am Water Resource Bulletin. 19(3): 415-419.
- Potts, D. F. 1984. Snow accumulation, melt and soil water recharge under various lodgepole pine stand densities in western Montana. In: Proceedings, 52nd Western Snow Conference; 1984 April 17-19; Sun Valley, ID. Fort Collins, CO: Colorado State University; July.
- Schmidt, R. A. and C. A. Troendle. 1989. Snowfall into a forest and clearing. Journal of Hydrology. 110(1989): 335-348.
- Schmidt, R.A. C.A. Troendle and J.R. Meiman. 1998. Sublimation of Snow pack in Sub Alpine Conifer forests. Canadian Journal of Forest Research. 28: 501-513
- Searcy, James K. and Clayton H. Hardison. 1960. Double-mass Curves. Manual of Hydrology: Part 1. General Surface – Water Techniques.

USGS Water Supply Paper 1541-B. U.S. Gov. Printing Office. 31-66.

Shepperd, W. D., C. A. Troendle, and C. B. Edminster. 1991. Linking Water and Growth and Yield Models to Evaluate Management Alternatives in Sub alpine Ecosystems. In: Proceedings. National Silviculture Workshop, 1991, May 6-9. Cedar City, UT. Gen. Tech. Rep. INT-291. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 42-49.

Stednick, John D. 1996. Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology*. 176: 79-95.

Troendle, C. A. 1983. The potential for water yield augmentation from forest management in the Rocky Mountain Region. *Am Water Resource Bulletin*. 19(3): 359-373.

Troendle, Charles A. 1983b. The Deadhorse experiment, a field verification of the sub alpine water balance model. Res. Note RM-425. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 7 p.

Troendle, C. A. 1987a. The Potential Effect of Partial Cutting and Stream flow from the Sub alpine Forest. Forest Service, Research Paper. Rocky Mountain Forest and Range Experiment Station, Gen. Tech. Rept. RM-274, Fort Collins, CO. 7 p.

Troendle, C. A. 1987b. Effect of Clear Cutting on Stream flow Generating Processes from a Sub alpine Forest. In: Swanson, R. H., P. Y. Bernier and Woodard, P.D. (Editors) *Forest Hydrology and Watershed Management*. Int. Assoc. Hydrol. Sci., Pub. No. 167, pp. 545-52.

Troendle, C. A. 1990. Coon Creek Water Yield Augmentation Project. In: Robert Z. Callaham, Technical Editor. Case Studies and Catalog of Watershed Projects in Western Provinces and States. Wild Land Resources Center. University of California at Berkeley. CA. Report 22. 21-23.

- Troendle, C. A. 1991. Global Change: Can we detect its effect on sub alpine hydrographs? In: Proceedings 59th Annual Western Snow Conference: 1991 April 12-15, Juneau, AK, Fort Collins, Colorado. Colorado State University 1-8.
- Troendle, C. A. and G. S. Bevenger. 1996. Effect of fire on stream flow and sediment transport, Shoshone National Forest, Wyoming. In: Ecological Implications of Fire in Greater Yellowstone. Jason Greenlee, Ed. International Assoc. of Wild Land Fire, Fairfield, VA. 43-45.
- Troendle, C. A. and M. R. Kaufmann. 1987. Influence of forests on the hydrology of sub alpine forests. In: Management of Sub alpine Forests: Building on Fifty Years of Research. Proceedings of a Technical Conference, Silver Creek, Colorado. July 6-9, 1987. U.S. Forest Service Gen. Tech Rep RM-149. 68-76.
- Troendle, C. A. and R. M. King. 1985. The effects of timber harvest on the Fool Creek watershed, 30 years later. Water Resource Research 21:1915-1922.
- Troendle, C. A. and R. M. King. 1987. The effect of partial and clear cutting on stream flow at Deadhorse Creek, Colorado. Journal of Hydrology. 90(1987): 145-157.
- Troendle, C. A. and C. F. Leaf. 1980. Hydrology. In: An approach to water resource evaluation of non-point silvicultural sources. EPA 600/18-80-012. Envir Res. Lab., Athens, GA. pp. III-1 - III-173.
- Troendle, C. A. and J. R. Meiman. 1984. Options for harvesting timber to control snow pack accumulations. In: Proceedings 52nd Western Snow Conference, 1984 April 17-19; Sun Valley, ID. Fort Collins, CO: Colorado State University. 86-97.
- Troendle, C. A. and J.R. Meiman, 1986. The effect of patch clear cutting on the water balance of a sub alpine forest slope. In: Proceedings, 54th Western Snow Conference; 1986 April 15-17; Phoenix, AZ. Fort Collins, CO: Colorado State University; 93-100.

- Troendle, C. A. and W. K. Olsen. 1994. Potential effects of timber harvest and water management on stream flow dynamics and sediment transport. In: Sustainable Ecological Systems: Implementing an Ecological Approach to Land Management, July 12-15, 1993, Flagstaff, AZ. – U.S. Forest Service Gen Tech Rep RM-247. 34-41.
- Troendle, C.A., R.A. Schmidt and M.H. Martinez. 1994. Partitioning the Deposition of Winter Snowfall as a Function of Aspect on Forested Slopes. In Eastern/Western Snow Conference; 1993 June 8-10; Quebec City, Quebec/Canada. Washington, DC/USA Western Snow Conference 61: 373-380
- Troendle, C.A. and J. D. Stednick. 1999. Discussion: “Effects of Basin Scale Timber Harvest on Water Yield and Peak Stream flow,” by Timothy A. Burton. JAWRA. 35(1): in press
- Troendle, C. A. and J. O. Reuss. 1997. Effect of clear cutting on snow accumulation and water outflow at Fraser, Colorado. Hydrology and Earth System Science. 1(2): 325-332.
- Troendle, C. A., M. S. Wilcox, and G. S. Bevenger. 1998. The Coon Creek Water Yield Augmentation Pilot Project. In: Proceedings 66th Western Snow Conference, April 21-23, 1998, Snowbird, Utah. Colorado State University, Ft. Collins, CO. 123-130.
- Van Haveren, B. P. 1988. A reevaluation of the Wagon Wheel Gap Forest Watershed Experiment. Forest Science. 34(1): 208-214.
- Wheeler, K. 1987. Interception and Redistribution of Snow in a Sub alpine Forest on a Storm-by-Storm Basis. Proc. 55th Western Snow Conference, Vancouver, B. C., pp. 78-87.
- Wilm, H. G. and E. G. Dunford. 1948. Effect of Timber Cutting on Water Available for Stream flow from a Lodgepole Pine Forest. USDA Technical Bulletin No. 968. 43 pp.